Energy efficiency evaluation for water supply systems in tall buildings

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Abstract

High-rise housing, a trend in densely populated cities around the world, increases energy use for water supply and corresponding greenhouse gas emissions. With emphasis on improving energy efficiency in water supply systems, this paper proposes an energy efficiency evaluation measure for water supply system designs and demonstrates its potential applications in a typical high-rise water supply system. In the proposed measure, energy efficiency in a water supply system is defined as the potential energy required at the demand locations divided by the pumping energy of the supply system. The outcome of this paper provides useful benchmark references for not only water supply system designs but also water demand management programmes in buildings.

Practical application: An energy efficiency evaluation measure for water supply system designs is used to establish benchmark references for not only water supply system designs but also water demand management programmes in buildings.

Keywords

Water supply, high-rise buildings, energy efficiency, benchmarks

Introduction

The water supply network is the largest single energy consumer in a city.[1] It was reported that in some developed cities, 40% of pumping energy is consumed inside buildings.[2,3] Improving energy efficiency of water supply systems in buildings is a way of reducing carbon emissions.[3]

In high-rise buildings, gravity storage tanks on the rooftops (or on intermediate mechanical floors) are designed for distributing water through down-feed pipes.[4,5] Pressure reducing valves (PRV) with adjustable settings and screwed joints are commonly installed to minimize the problems of water leakage or damages in the supply pipes and appliances caused by excessive water pressure on lower floors in low demand situations. In fact, pressurization that requires excessive energy or water pressure in a water supply system is a waste of energy.

Currently in Hong Kong, the average residential building height is estimated to be 26 storeys.[3] In response to the call for sustainable building designs, an energy efficiency evaluation measure, verified with measurements performed in some high-rise residential buildings in Hong Kong, has been proposed for designing water supply systems in buildings.[6] It was demonstrated that by relocating water storage tanks and avoiding overpressure at water demand points, energy efficiency of some high-rise water supply systems could be as high as 0.34 (the existing range is 0.20–0.25). To improve water

supply system performance, reducing friction in the supply pipes can be another significant contributor.[7]

[Insert Figure 1]

Methodology

Energy efficiency of a water supply system in high-rise buildings, which can be determined using the system heights (as shown in Figure 1), pipe friction and allowable pressure head, is defined as the potential energy required at the demand locations E_{out} divided by the pumping energy of the supply system E_{pump},[8]

$$\alpha = \frac{E_{out}}{E_{pump}} \tag{1}$$

E_{out} (MJ) is the potential energy for volumetric water demands v_i at height h_i as given below, where ρ (=1000 kgm^{-3}) is the water density and g (=9.81ms^{-2}) is the gravitational force,

$$E_{out} = \rho g \sum_{i=1}^{n} v_i h_i \tag{2}$$

Pumping energy of lifting water from the break tank to the roof tank E_{pump} (MJ) is defined in Equation (3), where η_c is the design overall transmission efficiency; h_l is the height difference between the break tank water surface and the roof tank inlet, which is also the sum of the height measured from the roof tank base to the tank inlet h_c, the height

difference between the demand n and the tank base h_b, and the height difference between the break tank water surface and the top demand location h_n; and H_o is the desired minimum water pressure head assumed at the roof tank inlet. H_f, the friction head required in the up-feed water pipe, is given by Equation (4), where f is the friction factor, u (ms^{-1}) is the flow velocity, d (m) is the hydraulic diameter and L_e is the pipe equivalent length taking all pipe fittings into account.[5]

$$E_{pump} = \frac{\rho g\left(h_l \sum_{i=1}^{n} v_i + H_f + H_o \right)}{\eta_c}; \quad h_l = h_c + h_b + h_n \tag{3}$$

$$H_f = f \frac{u^2}{2gd} L_e \tag{4}$$

It is noted that the design overall transmission efficiency η_c (34-65%) accounts for 50-80% of the pump efficiency η_p, about 90% of the mechanical transmission efficiency η_m and 70-90% of the electric motor efficiency η_e.[9,10]

$$\eta_c = \eta_p \eta_m \eta_e \tag{5}$$

The pump power P_t (kW) is given by,

$$P_t = \frac{q_o \left(H_f + H_o \right)}{100\, \eta_c} \tag{6}$$

By assuming a mass balance on the roof tank, the following equation can be used to determine the inflow rate of up-feed pipe q_o (Ls^{-1}) required to fulfil a time variant water

demand q_w (Ls^{-1}) within the time period of demand τ_∞, where V_∞ (L) is the total volumetric water consumption,[11]

$$V_\infty = \int_{\tau_\infty} q_w \, dt \le q_o \tau_\infty + V_o ; \quad \tau_\infty = t_\infty - t_0 \tag{7}$$

There are solution pairs (V_o, q_o) to Equation (7) at any time period within the time period of demand, $\tau_o \in \tau_\infty$.

$$V_o = \max\left\{ \int_{\tau_o} \left(q_o - q_w \right) dt \right\} \tag{8}$$

The required inflow rates for the minimum storage tank volume (V_o = 0) and the maximum storage tank volume ($V_o = V_\infty$) are $q_o = \max(q_w)$ and $q_o = q_{o,\infty}$ respectively,

$$q_o = \begin{cases} \max(q_w); & V_o = 0 \\ q_{o,\infty} \quad ; & V_o = V_\infty \end{cases} ; \quad q_{o,\infty} = \frac{V_\infty}{\tau_\infty} \tag{9}$$

The required inflow rate $q_{o,\infty} < q_o < \max(q_w)$ is dependent on the storage tank volume in terms of the water demand over any integration time period τ_o (s),

$$q_o = \frac{V_o}{\tau_o} \tag{10}$$

The water demand q_w (Ls^{-1}) is defined by a number of water appliances (i.e. 1,2,…,k) operating at any time $t \in \tau_\infty$,

$$q_w = \sum_k q_{c,k}(t) \tag{11}$$

Taking a flushing water system as an example, the demand period $t \in \tau_{w,l}$ (zero demand otherwise) is determined from the cistern demand flow rate q_c (Ls^{-1}) and cistern flushing volume V_c (L). q_c and V_c can be obtained from distribution functions $q_c \in \tilde{q}_c$ and $V_c \in \tilde{V}_c$ via the Monte-Carlo sampling technique. $\vartheta \in [0,1]$, a random number between 0 and 1 taken from a pseudo-random number set generated by a prime modulus multiplicative linear congruential generator, is expressed by,[12,13]

$$\vartheta = \int_{-\infty}^{q_c} \tilde{q}_c \, dq \; ; \quad \vartheta = \int_{-\infty}^{V_c} \tilde{V}_c \, dV \; ; \quad \tau_{w,l} = \frac{V_c}{q_c} \tag{12}$$

Operation of an appliance is random within a time period τ_w (s) which starts at time $t_{w,0}$ (s) and ends at time $t_{w,\infty}$ (s); it equals to the sum of time periods of non-zero demands $\tau_{w,l}$ (s) and zero demands $\tau_{0,l}$ (s) for l=1,2,…,N_a, where N_a (h^{-1}) is the hourly demand of an appliance within the time period and the time periods are represented by the appliance demand start time $t_{w1,l}$ (s) and the appliance demand end time $t_{w2,l}$ (s),[11]

$$\tau_w = t_{w,\infty} - t_{w,0}$$

$$= \begin{cases} \tau_{0,1} + \tau_{w,1} + \tau_{0,2} + \tau_{w,2} + \cdots + \tau_{0,l} + \tau_{w,l} + \cdots + \tau_{0,N_a} + \tau_{w,N_a} + \tau_{0,N_a+1} & ; \quad t_{w2,N_a} \le t_{w,\infty} \\ \tau_{w,0} + \tau_{0,1} + \tau_{w,1} + \tau_{0,2} + \tau_{w,2} + \cdots + \tau_{0,l} + \tau_{w,l} + \cdots + \tau_{0,N_a} + \tau_{w,N_a} - \tau_{0,N_a+1} & \quad t_{w2,N_a} > t_{w,\infty} \end{cases} \tag{13}$$

$$\tau_{0,l} = t_{w1,1} - t_{w2,l-1} \; ; \quad \tau_{w,l} = t_{w2,l} - t_{w1,l} \tag{14}$$

$$\tau_{0,1} = \begin{cases} t_{w1,1} - t_{w,0} \\ t_{w1,1} - t_{w2,0} \end{cases} ; \quad \tau_{0,N_a+1} = \begin{cases} t_{w,\infty} - t_{w2,N_a} & ; \quad t_{w2,N_a} \le t_{w,\infty} \\ t_{w2,N_a} - t_{w,\infty} = t_{w2,0} - t_{w,0} = \tau_{w,0} & \quad t_{w2,N_a} > t_{w,\infty} \end{cases} \tag{15}$$

The demand start time $t_{w1,l}$ (s) is given by a randomly distributed fractional demand start time $\hat{t}_{w1,l}$ (s) and can be determined via Monte Carlo simulations using a uniformly distributed fractional demand start time U (s),

$$t_{w1,l} = \hat{t}_{w1,l}\tau_w \; ; \vartheta = \int_{-\infty}^{\hat{t}_{w1,l}} U \, dt \tag{16}$$

The hourly demand N_a (h^{-1}) of an appliance is given by the following equation, where n_a ($person^{-1}h^{-1}$) is the hourly demand per person, N_p (persons) is the number of persons at a time expressed through an occupant load variation factor $\phi(t)$, and $N_{p,max}$ (persons) is the maximum occupant load of appliance designated for serving an apartment floor area A_f (m^2) and determined via the occupant-area ratio O_a (person m^{-2}),[14]

$$N_a(t) = n_a N_p(t) = n_a N_{p,max}\phi(t) = n_a O_a A_f \phi(t) \tag{17}$$

Figures 2 and 3 exhibit the per-person hourly usage patterns and occupant load variations of a residential water closet (WC) respectively. The hourly demand N_a for each WC serving $N_{p,max}$=4.2 persons is shown in Figure 4.[14,15]

[Insert **Figure 2**]

[Insert **Figure 3**]

[Insert **Figure 4**]

[Insert **Figure 5**]

Simulations

As appliance operations is random, the time series of demand flow rates $q_w(t)$ was simulated using Equation (11) in terms of maximum and minimum daily volumetric consumption $\int_{\tau_\infty} q_w \, dt$ for 100 years operations of the water supply system. The simulation results are shown in Figure 5, with input parameters in Figures 1–4 using Equations (13)–(17) via the Monte-Carlo sampling technique described by Equation (12). The procedures were coded and executed in an i7 machine, and the executing time was about one week per simulation case. Results in Figure 5(a)&(b) indicated that the simulated daily consumption range was 76.1 m^3d^{-1} to 81.9 m^3d^{-1}, with an average of 78.9 m^3d^{-1} calculated from all simulation days.

Figure 6(a) illustrates the solution pairs (V_o, q_o) given by Equation (10) for the demand time series shown in Figure 5(a) with respect to demand periods τ_o=1, 60 and 300s. The results showed that a coarse integration time period τ_o (e.g. 300s) for the simulation may not give an accurate solution for small storage volume, however, no significant difference was found for the simulation results among integration demand periods τ_o=1, 10 and 60s as shown in Figures 6(a)&(b). Some differences in range of small storage volume was found for longer integration demand time period of 300s as demonstrated in Figure 6(a). At a minimum storage volume of 250 L (Hong Kong practice), the simulated inflow rates were from 1.907 to 1.924 Ls^{-1} for Figure 5(a) and equalled to 1.76 Ls^{-1} for Figure 5(b).

These inflow rates do not pose significant practical concerns about specifying the inflow rates required for general engineering applications as safety margins are normally imposed when selecting a water pump to feed the storage tank. The minimum flow rates for the cases shown in Figures 6(a) and 6(b) were 0.95 $Ls^{-1}$and 0.88 Ls^{-1} respectively.

[Insert **Figure 6**]

Illustration applications

As the water pressure head at the government water mains in Hong Kong is insufficient to reach the topmost appliances in almost all high-rise buildings, gravity storage tanks on building rooftops (or on intermediate mechanical floors) are commonly designed for distributing water through down feed pipes.[8] An example of high-rise tank water supply system for 600 residential WC cisterns is presented in Table 1.[16] Design inflow rates were determined for the design and installed conditions and then compared with cases using some existing design practices.[5] As the design inflow rate under the installed conditions allowed a much greater margin of safety (of 30%) than the one under the design conditions, a larger pump was selected for the installed system. In the base case, the roof tank was fed by a pump at the design flow rate through a 67-mm-diameter pipe. The total static head for h_l=100 m was counted and a friction head loss H for an equivalent pipe length h_{fo}=150 m was included. To determine the system efficiencies, an average height

of demand locations h_d=50 m and an overall pump efficiency η_c=0.5625 were applied. Equation (1) becomes,

$$\alpha = \frac{H_d \eta_c}{H_{fo} + h_l} \tag{18}$$

To determine the pumping energy, Equation (19) was used.

$$E_{pump} = \frac{\rho g V \left(H_{fo} + h_l \right)}{\eta_c} \tag{19}$$

Table 1 shows that system efficiency of the installed system decreased from 0.243 (design value) to 0.235, corresponding to an efficiency drop of 3% or an extra energy consumption of 3.1%. It is the result of a higher friction head loss in the pipelines caused by a higher water velocity than the design value.

Table 1. An example of high-rise tank water supply system for 600 residential WC cisterns

Parameters	Roof-tank system (Design)	Roof-tank system (Installed)	Variable speed pumping system	Intermediate-and-roof-tank system
Total tank size (m^3)	0.25-27	0.25-27	0.25-27	0.5-27
Daily consumption (m^3)	76-82	76-82	76-82	76-82
Design inflow rate (Ls^{-1})	5.1	6.6	0.95-1.9	3.2
Base case*				
Feed pipe water velocity (ms^{-1})	1.5	1.9	0.3-0.5	0.9
Friction head loss (m)	16.0	19.6	10.4-11.2	11.4-12.7
System efficiency	0.243	0.235	0.253-0.255	0.302
Total electricity power (kW)	10.5	14.1	1.9-3.8	9.9
Daily pumping energy (kWh)	43-46	44-48	41-44	32-35
Case A: Exit static head reduced by 50%				
Feed pipe water velocity (ms^{-1})	1.5	1.9	0.3-0.5	0.9
Friction head loss (m)	11.0	14.6	5.4-6.2	6.4-7.7
System efficiency	0.253	0.245	0.265-0.267	0.321
Total electricity power (kW)	10.1	13.5	1.8-3.6	9.3
Daily pumping energy (kWh)	41-44	42-46	39-42	30-33
Case B: Building height increased by 50%				
Feed pipe water velocity (ms^{-1})	1.5	1.9	0.3-0.5	0.9
Friction head loss (m)	19.0	24.4	20.6-11.8	12.0-14.1
System efficiency	0.250	0.242	0.261-0.263	0.314
Total electricity power (kW)	15.3	20.6	2.7-5.5	14.3
Daily pumping energy (kWh)	62-67	64-69	59-64	46-50
Case C: Supply pipe diameter one size down (i.e. 54 mm)				
Feed pipe water velocity (ms^{-1})	2.2	2.9	0.4-0.8	1.4
Friction head loss (m)	27	34	10.9-13.0	13.4-16.8
System efficiency	0.222	0.210	0.249-0.254	0.292
Total electricity power (kW)	11.5	15.8	1.9-3.8	10.3
Daily pumping energy (kWh)	47-50	49-53	41-45	33-36

* Base case: Building height = 100 m; Exit static head loss = 10 m; Feed pipe = 67 mm in diameter, with an equivalent length of 1.5 times the building height.

To achieve the design flow rate, variable speed control is a solution. Based on the mass balance assumption presented in the previous section, the relationship between inflow rate to the tank and size of the tank determined for the usage patterns is graphed in Figure 6. Taking a daily consumption range from 76m^3 to 82 m^3, the design flow rate is from 0.95 L/s (at a tank size of 27 m^3) to 1.9 L/s (at a tank size of 0.25 m^3) for fulfilling the water demands in some residential buildings.[9] As the efficiency of a variable speed pumping system can be increased to 0.255, corresponding to 5.1% pumping energy savings compared with the design system, energy loss due to system friction in high-rise pumping can be significant and system friction optimization should not be ignored in the future designs of tank water supply network.

Zoning a high-rise water supply system by an intermediate tank can limit the system pressure and thus reduce the pumping energy. As exhibited in Table 1, the efficiency of an intermediate-and-roof tank system can be as high as 0.302, corresponding to 24% pumping energy savings.

In contrast to the base-case scenario, three cases namely A, B and C are illustrated in Table 1 to demonstrate the effects of different design values on system efficiency with graphically illustrated in Figure 7.

In Case A, the exit static head loss of the roof tank inlet was reduced by 50% at the same supply flow rate. Energy loss reduction was represented by a system efficiency drop from 6.2% in the base case to 4.4% in this case.

For Case B, a building which was 50% taller than the one in the base case was employed under the same water supply design conditions. In this case, the exit friction head loss did not increase proportionally with the building height, and the system efficiency increased slightly as compared to the base case. Therefore, at the same supply flow rate, potential energy savings can be achieved by using water appliances with low pressure loss.

Case C was a water supply system with a smaller up-feed pipe, one size down from 67 mm to 54 mm in diameter. Significantly increased friction loss in the pipe resulted in 8.3% system efficiency drop under the design conditions or 10.7% under the installed conditions, as compared to the base case. A less significant influence on the intermediate-and-roof tank system, where the design flow rate was lower, was found (–3.4%). Less impact on energy efficiency (from –0.5% to –1.6%) was also shown for the intermediate-and-roof tank system. Although the total storage volume remains unchanged, it is noted that additional intermediate tank with separate pump sets require additional cost. The installation would be cost justified with short payback periods.[17]

[Insert **Figure 7**]

Conclusion

With emphasis on improving energy efficiency in water supply systems, this paper proposed an energy efficiency evaluation measure for water supply system designs and demonstrated its potential applications in a typical high-rise water supply system. In the proposed measure, energy efficiency in a water supply system is defined as the potential energy required at the demand locations divided by the pumping energy of the supply system. The outcome of this paper provides useful benchmark references for not only water supply system designs but also water demand management programmes in buildings.

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References

1. Plappally AK and Lienhard JH. Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews* 2012; 16: 4814-4848.

2. Cheng CL. Study of the inter-relationship between water use and energy conservation for a building. *Energy and Buildings* 2002; 34(3): 261–266.
3. Shimizu Y, Toyosada K, Yoshitaka M and Sakaue K. Creation of Carbon Credits by Water Saving. *Water* 2012; 4: 533-544.
4. Cheung CT, Mui KW and Wong LT. Energy implications for water supply tanks in high-rise buildings. *The 38th CIBW062 International Symposium of Water Supply and Drainage for Buildings*, 27-30 August 2012, Edinburgh, Scotland, UK.
5. Plumbing Services Design Guide. The Institute of Plumbing. England: Hornchurch, 2002.
6. Wong LT, Cheung CT and Mui KW. Energy efficiency benchmarks of example roof-tank water supply system for high-rise low-cost housings in Hong Kong. *The 39th CIBW062 International Symposium of Water Supply and Drainage for Buildings*, 17-20 September 2013, Nagano City, Japan.
7. Wong LT, Mui KW and Cheung CT. Minimum pumping energy of tree-shaped water supply networks for probabilistic demands in built environment. *Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition (IMECE2012)*, 2012, Houston Texas, USA. (IMECE2012-85908).
8. Cheung CT, Mui KW and Wong LT. Energy efficiency of elevated water supply tanks for high-rise buildings. *Applied Energy* 2013; 103(3): 685-691.

9. Kaya D, Yagmur EA, Yigit KS, Kilic FC, Eren AS and Celik C. Energy efficiency in pumps. *Energy Conversion and Management* 2008; 49(6): 1662–1673.
10. Wong LT, Mui KW, Lau CP and Zhou Y. Pump efficiency of water supply systems in buildings of Hong Kong. *Energy Procedia* 2014; 61: 335-338.
11. Mui KW and Wong LT. Modelling occurrence and duration of building drainage discharge loads from random and intermittent appliance flushes. *Building Services Engineering Research and Technology* 2013; 34(4): 381-392.
12. Wong LT and Mui KW. Stochastic modelling of water demand by domestic washrooms in residential tower blocks. *Water and Environment Journal* 2008; 22: 125–130.
13. Park SK and Miller KW. Random number generators: good ones are hard to find. *Communications of the ACM* 1988; 31(10): 1192–1201.
14. Wong LT and Mui KW. An epistemic analysis of residential occupant load factor. *Proceedings of Zhejiang-Hong Kong Joint Symposium 2007 – Innovative Building Design and Technology-Challenges of Climate Change*, 6-7 July 2007, Hangzhou, China, pp. 38–44.
15. Wong LT and Liu WY. Demand analysis for residential water supply systems in Hong Kong. *HKIE Transactions* 2008; 15(2): 24–28.

16. Wong LT, Mui KW and Zhou Y. An energy efficiency evaluation measure of water supply systems for high-rise buildings. *The 4th International Technical Conference on Hydraulic Engineering*, 16-17 July 2016, Hong Kong, China.
17. Wong LT, Zhou Y, Mui KW, Lau CP. Optimizing water supply pump replacement in buildings of Hong Kong. *Building Services Engineering Research and Technology* 2015; 37(4) 489–498..

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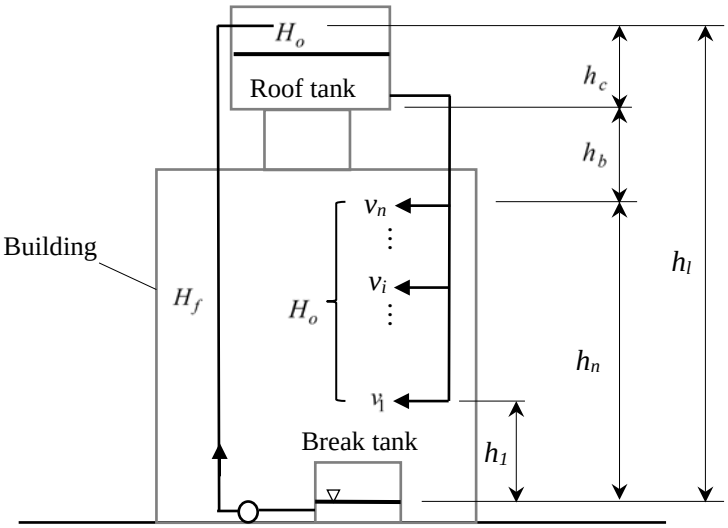

Figure 1. A high-rise gravity tank water supply system

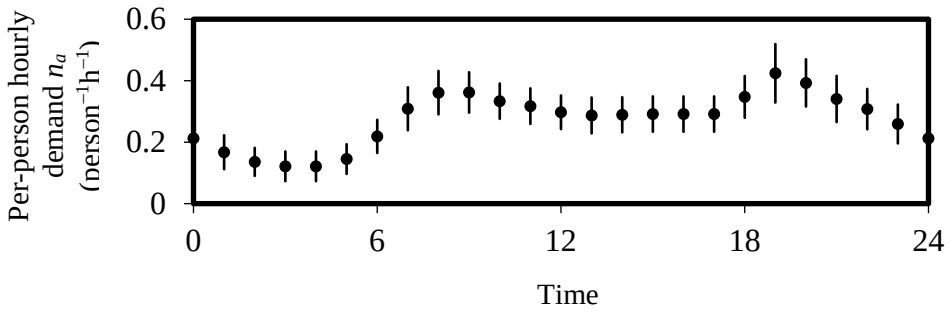

Figure 2. Per-person hourly WC demand n_a

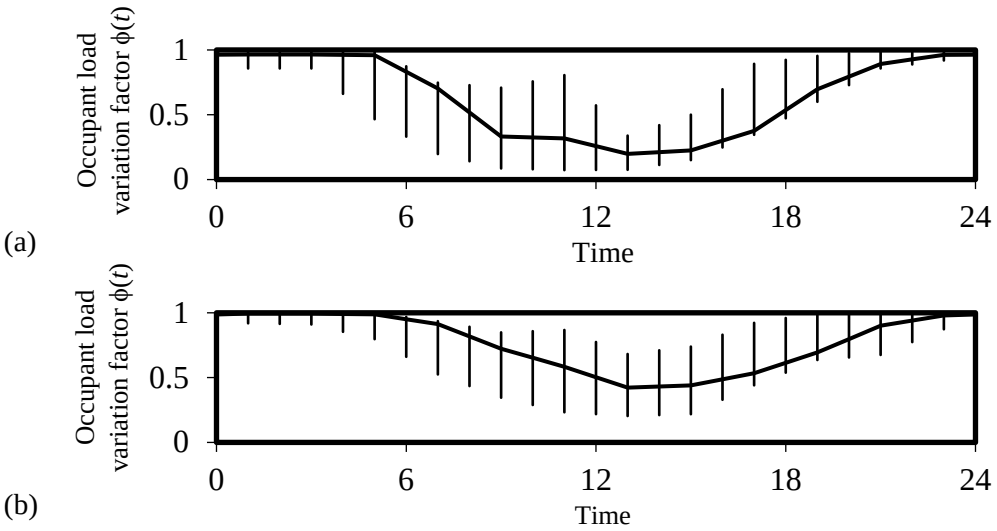

Figure 3. Occupant load variation factor $\phi(t)$: (a) weekdays; (b) holidays

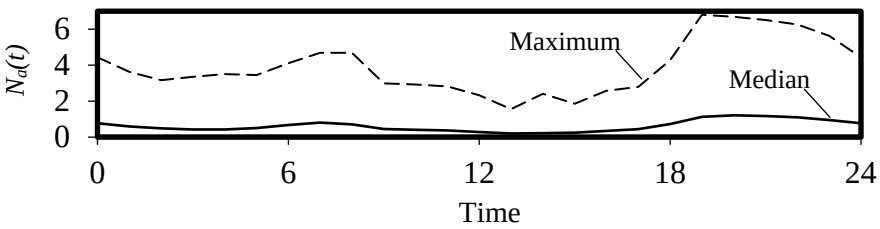

Figure 4. Hourly demand of each WC

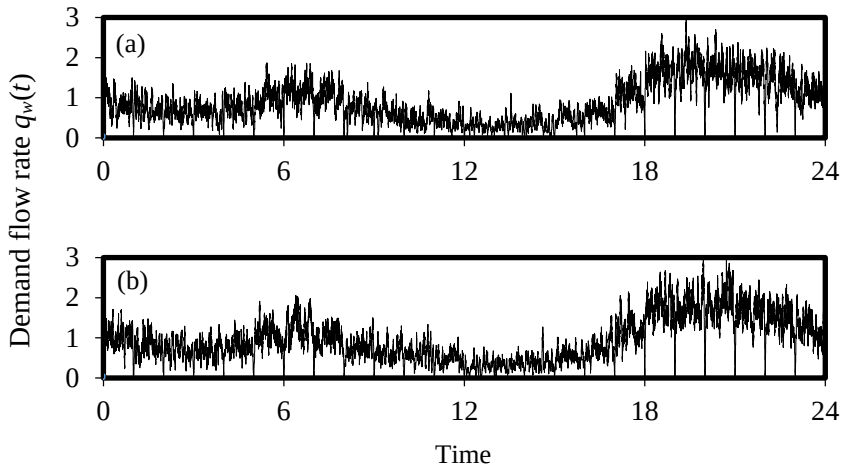

Figure 5. Example demand flow rates for 600 WCs: (a) maximum daily consumption (81.9 m^3d^{-1}); (b) minimum daily consumption (76.1 m^3d^{-1})

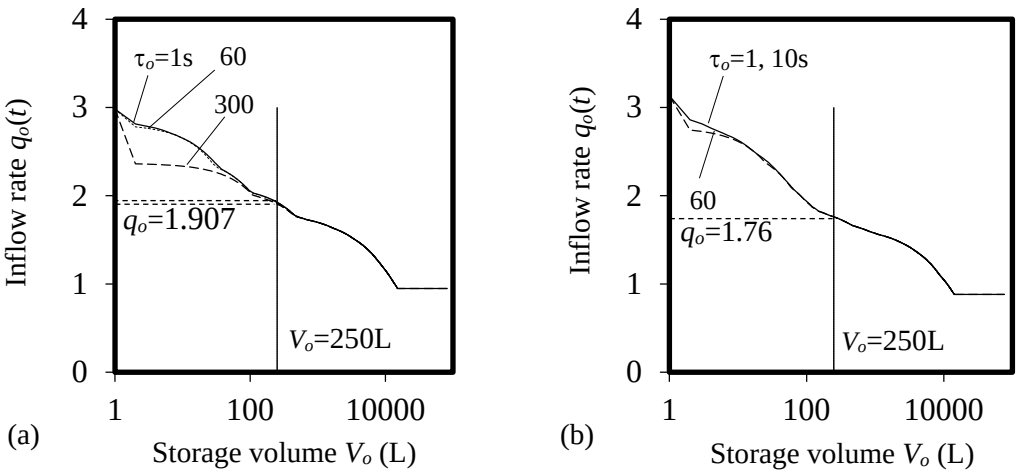

Figure 6. Solutions of inflow rate and storage volume for the minimum and maximum demand time series

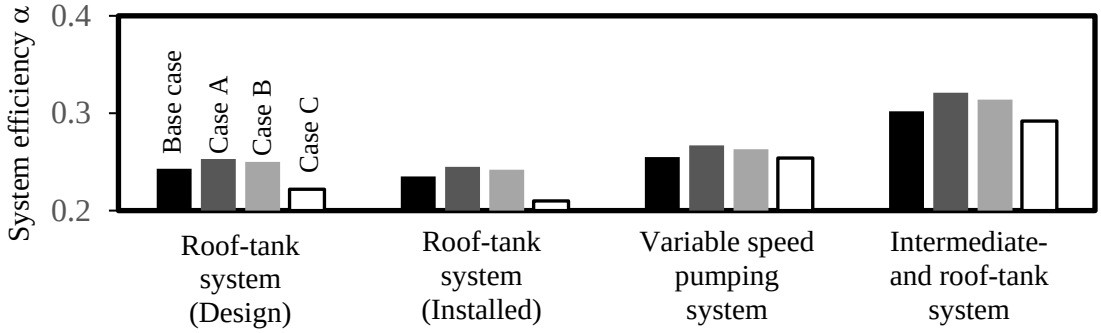

Figure 7. Summary of system efficiencies