Energy efficiency benchmarks of example roof-tank water supply system for high-rise low-cost housings in Hong Kong

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Abstract

Energy efficiency of water supply systems in high-rise residential buildings becomes a concern for sustainable development nowadays. The energy efficiency for water supply system operation is the potential energy of the water demands in buildings divided by the pumping energy required. Water supply is a basic and essential facility for buildings and elevated storage tanks are typically installed to ensure a reliable supply in low-cost housings in Hong Kong. This paper presents mathematical expressions for energy efficiency of water supply system and evaluates the energy efficiency for buildings with non-uniform water demands at floors. Energy efficiency determined for example water supply systems of high-rise low-cost housings in Hong Kong could serve as useful benchmark references for demand management programme for buildings.

Keywords

Water supply, buildings, energy, efficiency, benchmarks

1 Introduction

About half of residents in Hong Kong living in government funded and subsidized housings. Developments of tall buildings are a recent trend in cities. Energy efficiency of water supply becomes a concern for sustainable development nowadays. Pumping energy of 0.08 MJ per cubic meter is required to lift water per additional one storey of building [1]. However, energy efficiency measures accounted for various building
demand patterns as well as energy consumption data readily for benchmarking purposes are still lacking.

This paper proposes an energy efficiency measure for water supply system to determine energy efficiency benchmarks for buildings of various water demand patterns [2]. Roof-tank water supply system is a typical design for common high-rise low-cost residential buildings and is taken as a simple means to illustrative the applicability of the proposed measure. The usefulness of energy efficiency benchmarks is also discussed for water demand management in high-rise low-cost residential buildings.

![Figure 1 - Roof tank water supply systems in buildings](image)

### 2 Energy efficiency

Energy efficiency of roof storage tank water supply system in high-rise buildings is defined as the required potential energy $E_{\text{out}}$ divided by the pumping energy $E_{\text{pump}}$ of the supply system for a volumetric water demand in buildings. It can be determined for the water supply systems using the system heights, pipe friction and allowable pressure head as in Figure 1 (a roof tank water supply system) for maintaining water supply appliance operation [2],

$$\alpha = \frac{E_{\text{out}}}{E_{\text{pump}}}$$  \hspace{1cm} (1)

$E_{\text{out}}$ (MJ) is the potential energy for the volumetric water demands $v_i$ at height $h_i$ is given below, where $\rho (=1000 \text{ kgm}^{-3})$ is the water density and $g (=9.81 \text{ ms}^{-2})$ is the gravity.
The pumping energy of lifting water up from the break tank to the roof tank $E_{\text{pump}}$ (MJ) is defined below, where $\eta_c$ is the design overall transmission efficiency, where $h_l$ is the height difference between the break tank water surface and the roof tank inlet, which is 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 $h_n$, $H_f$ is the desired minimum water pressure head assumed at the demand point and $H_f$ is the friction head required in the upfeed water pipe,

$$E_{\text{pump}} = \frac{\rho g \left( h_l \sum_{i=1}^{n} v_i + H_f + H_o \right)}{\eta_c}$$

$$h_l = h_c + h_b + h_n$$

The energy per volumetric water consumption $e$ is an indicator of engineering design and is expressed below,

$$e = \frac{E}{v}; \ v = \sum_{i=1}^{n} v_i$$

It is noted for the design overall transmission efficiency $\eta_c$ (34-65%) accounted for 50-80% of the pump efficiency $\eta_p$, about 90% of the mechanical transmission efficiency $\eta_m$ and 70-90% of the electricity motor efficiency $\eta_e$. For simplicity, constant efficiencies are assumed: $\eta_p=0.65$, $\eta_m=0.9$, $\eta_e=0.9$ and $\eta_c=0.5265$ [3],

$$\eta_c = \eta_p \eta_m \eta_e$$

The average daily water consumption on a floor $v_{i,d}$ is determined by, where $N_{s,i}$ is the number of occupants on floor $i$, $v_{s,d}$ is the average daily per-capita water consumption, $O_{s,i}$ is the occupant area ratio on floor $i$ and $A_i$ is the total apartment area on floor $i$ [4],

$$v_{i,d} = N_{s,i} v_{s,d}; \ N_{s,i} = O_{s,i} A_i$$

Regional profiles of occupant area ratio $O_s$ and average daily per-capita water consumption $v_{s,d}$ in buildings by parametric distribution functions as shown in Table 1. Parameters $v_{s,d}$ and $O_{s,i}$ can be determined via Monte Carlo simulations at percentile $v_{s,d}$, $O_{s,i}$ =9 [0,1] through the distribution functions $\tilde{v}_{s,d}$ and $\tilde{O}_s$, where $\theta$ is a random number taken from a pseudo random number set generated by the prime modulus multiplicative linear congruential generator [5].

$$\int_{-\infty}^{v_{s,d}} \tilde{v}_{s,d} dv_{s,d} = \theta \in [0,1]; \int_{-\infty}^{O_{s,i}} \tilde{O}_s dO_s = \theta \in [0,1]; \ v_{s,d} \in \tilde{v}_{s,d}; \ O_{s,i} \in \tilde{O}_s$$
Table 1 Selected number of design parameters for building water supply systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump efficiency $\eta_p$</td>
<td>0.65</td>
</tr>
<tr>
<td>Mechanical transmission efficiency $\eta_m$</td>
<td>0.90</td>
</tr>
<tr>
<td>Electric motor efficiency $\eta_e$</td>
<td>0.90</td>
</tr>
<tr>
<td>Total water storage tank volume $V_c$ (m$^3$)</td>
<td>65</td>
</tr>
<tr>
<td>Height between tank base and the last demand location $h_b$ (m)</td>
<td>6</td>
</tr>
<tr>
<td>Height of the bottom demand location $h_i$ (m)</td>
<td>3.6</td>
</tr>
<tr>
<td>Height of the top demand location $h_n$ (m)</td>
<td>$\geq$10</td>
</tr>
<tr>
<td>Height of the tank inlet measured from tank base $h_c$ (m)</td>
<td>4</td>
</tr>
<tr>
<td>Friction head loss in pipes $H_f$ (m)</td>
<td>0.1$h_i$</td>
</tr>
<tr>
<td>Minimum water pressure head allowed at the outlet $H_o$ (m)</td>
<td>10</td>
</tr>
<tr>
<td>Building floor-to-floor height (m)</td>
<td>2.6</td>
</tr>
<tr>
<td>Occupant area ratio $O_s$ (ps m$^{-2}$)</td>
<td>0.085 (0.03)</td>
</tr>
<tr>
<td>(public residential)</td>
<td></td>
</tr>
<tr>
<td>Yearly per-capita water consumption (m$^3$ ps$^{-1}$ year$^{-1}$) (freshwater)</td>
<td>70 (13)</td>
</tr>
<tr>
<td>(seawater for flushing)</td>
<td>22 (10)</td>
</tr>
</tbody>
</table>

Standard deviation shown in brackets

2.1 Model validity

Daily electricity consumptions of water supply systems in 22 government-funded low-cost residential buildings of Hong Kong were used to examine the validity and applicability of the proposed water demand model and the energy efficiency measure. The buildings varied from 15 to 40 storeys (with an average height of 29 storeys), provided from 300 to 800 apartments at floor areas between 16 to 63 m$^2$. Water secured from the city mains was stored in a break tank and transferred through a pair of transfer
pumps to the rooftop gravity tanks for distribution to every floor of the building. Figure 2 shows the predicted daily pumping energy consumption (Eq. 3) against the measured one for the surveyed buildings. Probable errors of measurement were taken at a half of the energy required to fill up the tank as a single-day energy consumption monitoring period might fall between two roof tank filling cycles. The predictions, which were based on typical pump efficiency details displayed in Table 1, reasonably agreed with the measurement results (P<0.0001, t-test).

3 Energy benchmarks

The values of energy efficiency \( \alpha \) for high-rise roof-tank water supply systems using the design numbers in Table 1 is approaching 0.24 with an increased height, with uniformly distributed water consumption at building floors,

\[
\alpha = \frac{\eta_c \left( \frac{h_n + h_i}{2} \right)}{H_o + \left( h_n + h_o + h_i \right) + H_f} = \frac{\eta_c (h_n + 3.6)}{42 + 2.2h_n} ; h_n \to \infty : \alpha \sim \frac{\eta_c}{2.2} = 0.24 \quad \ldots (8)
\]

For an example building of 40 levels corresponding to \( h_n = 3.6(40-1) = 101.4 \) m, the energy efficiency is \( \alpha = 0.23 \), \( e_{out} = 9800 \times \sum_{i=1}^{n=40} h_i / 40 = 0.53 \), \( h_f = 3.6 + 2.6(i-1) \) and the expected per-volume pumping energy is \( e_{pump} = 0.53/0.23 = 2.3 \text{ MJ m}^{-3} \). This value could be an indicative energy efficiency benchmark of the building water supply system. For the system consumed more energy, it explicitly operates at a less efficiency manner which cannot achieve the specified efficiencies as shown in Table 1.

However, the application of this indicative benchmark is limited. Water consumptions at building with \( n \) apartment floors can be non-uniformly distributed due to non-uniform occupant load and/or different water consumption patterns of occupancy.

3.1 Non-uniform water consumption patterns

The total consumption of a building is represented by the unit height apartment consumption \( c_{d,v}^* \) and is calculated by the product of unit apartment height \( h^* \) and the unit daily apartment water consumption \( v^* \), i.e. \( v^* h^* \).

For demonstration the use of energy efficiency as an indicator of building designs, a step function of consumption along the building height is assumed and the total daily water consumption of the building \( c_{d,v}^* \) is remaining unchanged, i.e. \( v^* h^* = c_{d,v}^* \), where \( c_{d,v,1}^* \) and \( c_{d,v,2}^* \) are constant daily apartment water consumptions at level \( i \), \( c_i \) is the arbitrary building level,
Figure 3 exhibits various configurations of water consumptions in an example high-rise low-cost building of 400 apartment units. Each unit has an apartment height of 2.6 m and floor area of 40 m² expected to accommodate 3.4 residents, corresponding to an apartment unit water consumption of 0.86 m³ d⁻¹. The average daily water consumption of the building is 343 m³ d⁻¹.

The configurations in Figure 3 are grouped into 2 cases (I)&(II) and presented mathematically below for sub-cases $j=1,2,...11$,

(I): $c_{dv}^* = 400$ ; $n = 40$ ; $c_i = 20$ ; $c_{dv,1,j}^* = 2(j-1)$ ; $c_{dv,2,j}^* = 2(11-j)$ ; $j = 1,2,...11$  

(II): $c_{dv}^* = 400$ ; $n_j = 40 - 2(j-1)$ ; $c_{i,j}^* = 2(j-1)$ ; $c_{dv,1}^* = 10$ ; $c_{dv,2}^* = 20$ ; $j = 1,2,...11$

Procedures described in Eqs.(6)&(7) with input parameters in Table 1 were applied for simulations for cases (I)&(II) and corresponding energy efficiency is determined using Eqs. (1) to (3).
Figures 4&5 exhibit the energy consumptions and efficiency of fresh and flushing water supply systems at water consumption distributions for case (I) a building of a constant height and (II) a building of different height. In the figures, the results are plotted against the distribution ratio of water consumption in building height $\zeta_v$ given by an expression below,

$$
\zeta_v = \frac{c_1^{*} (n - c_i) - c_2^{*} c_i}{c_3^{*}} 
$$

... (12)

![Figure 4](image)

**Figure 4** - Results of case (I) against water consumption ratio. (a) Daily energy consumption (MJ d$^{-1}$); (b) Energy consumption per water consumption (MJ m$^{-3}$); (c) Energy efficiency $\alpha$; (d) Energy variation $\zeta_E$. 

- • Flushing water
- o Fresh water

$E_{\text{pump}}$  
$E_{\text{out}}$
Flushing water

Fresh water

Figure 5 - Results of case (II) against height ratio. (a) Daily energy consumption (MJ d\(^{-1}\)); (b) Energy consumption per water consumption (MJ m\(^{-3}\)); (c) Energy efficiency \(\alpha\); (d) Energy variation.

The pumping energy consumption \(E_{\text{pump}}\) remains constant for various configurations for case (I) because the building height remains unchanged but an increased consumption for case (II) is reported for increased building height. It is obvious that the potential energy \(E_{\text{out}}\) increase as higher portion of water demands reported at high levels of the building.

It is also noted that the configuration of sub-cases (I)\(_6\) and (II)\(_1\) are identical and of almost a uniform water consumption distribution. The two cases can be approximated directly using Eqs. (3) and (8). The simulation results (\(e_{\text{pump}}=2.33\) MJ m\(^{-3}\), \(\alpha=0.233\)) shown in Figures 4(b)&5(b) are closed to the values determined by the equations (\(e_{\text{pump}}=2.3\) MJ m\(^{-3}\) and \(\alpha=0.23\)).
Figures 4(c)&5(c) show very different range of energy efficiency for the two cases: (I) 0.12-0.34 and (II) 0.19-0.23. It is prominent that higher energy efficiency is reported for cases of the roof tank vertically close to the water demands. Pressure head due to the elevated tank are sufficient but not over pressurize the appliances of the water demand point. However, for those cases of lower efficiencies, more appliances are over pressurized and pressure reducing facilities are installed. The proposed parameter ‘energy efficiency’ indicates the wastage of pressure head due to the system design.

In Figures 4(c)&5(c), the higher and lower bounds of the energy efficiency shown in the figures are determined by one standard deviation \( \sigma \) from the average simulated value \( \mu \). The bounds reflect variations of water demands due to occupants. The corresponding variations of energy are shown in Figures 4(d)&5(d) by plotting energy variations expressed by an expression below,

\[
\zeta_E = \frac{\sigma_E}{\mu_E}
\]

(13)

The energy variations are 2-4% and trend is shown for case (II). A larger deviation is reported for water demands spread over the building height. The deviation is reduced for water demands concentrated at some building levels rather than uniformly distributed water demands.

4 Conclusion

Energy efficiency in buildings is a sustainable development strategy. It is necessary to develop a method to systematically address energy efficiency with respect to the optimal design of high-rise water supply systems. This paper develops an evaluation measure of energy efficiency, i.e. which is the potential energy of the water demands in buildings divided by the pumping energy of the supply system, for some water supply system designs with roof tanks at high-rise low-cost housings in Hong Kong. The parameter was demonstrated to be useful for evaluating designs that integrate energy consumption into urban water planning processes which cater to various building demands and non-uniform usage patterns. The results showed that the energy efficiency of some high-rise water supply systems was up to 0.24 and could be as high as 0.34 for avoiding over pressure at water demand points. This paper determines energy efficiency benchmarks for example water supply systems of high-rise low-cost housings in Hong Kong which could serve as useful references for demand management programme for in buildings.

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List of symbols

\[ A \] Area (m\(^2\))
\[ c \] Constant
\[ E \] Energy (MJ)
\[ e \] Per unit energy consumption (MJ/m\(^3\))
\[ g \] Gravity (=9.81 ms\(^{-2}\))
\[ H \] Pressure head of water column (m of H\(_2\)O)
\[ h \] Height (m)
\[ i, j \] Dummy variables as defined
\[ N \] Number count
\[ O \] Occupant area ratio (ps m\(^{-2}\))
\[ P \] P-value of a specified statistical test
\[ V \] Volume (m\(^3\))
\[ v \] Volumetric water demand over a specified period (m\(^3\))
\[ \varnothing \] Random number between 0 and 1
\[ \alpha \] Energy efficiency
\[ \eta_c \] Overall transmission efficiency
\[ \eta_e, \eta_m, \eta_p \] Efficiency for electric motor, mechanical transmission and pump
\[ \mu \] Average
\[ \rho \] Water density (=1000 kgm\(^{-3}\))
\[ \sigma \] Standard deviation
\[ \zeta \] Ratio

Subscript
\[ 1,2,\ldots,n \] of 1,2,\ldots-\(n\)-th conditions
\[ b \] of water tank base
\[ c \] of water tank base to inlet
\[ d \] of daily
\[ E \] of energy
\[ f \] of friction in upfeed water pipe
\[ l \] of water lift between break tank water surface and roof tank inlet
\[ o \] of outlet
\[ out \] of output
\[ pump \] of water pump
\[ s \] of occupant
\[ v \] of volumetric water demand

Superscript
\[ \sim \] of distribution
\[ * \] of unit value
5 References


6 Presentation of Authors

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