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Energy efficiency of elevated water supply tanks for high-rise buildings

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HIGHLIGHTS

- ▶ We evaluate energy efficiency for water supply tank location in buildings.
- ▶ Water supply tank arrangement in a building affects pumping energy use.
- ▶ We propose a mathematical model for optimal design solutions.
- ▶ We test the model with measurements in 22 Hong Kong buildings.
- ▶ A potential annual energy saving for Hong Kong is up to 410 TJ.

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ABSTRACT

High-rise housing, a trend in densely populated cities around the world, increases the energy use for water supply and corresponding greenhouse gas emissions. This paper presents an energy efficiency evaluation measure for water supply system designs and a mathematical model for optimizing pumping energy through the arrangement of water tanks in a building. To demonstrate that the model is useful for establishing optimal design solutions that integrate energy consumption into urban water planning processes which cater to various building demands and usage patterns, measurement data of 22 high-rise residential buildings in Hong Kong are employed. The results show the energy efficiency of many existing high-rise water supply systems is about 0.25 and can be improved to 0.26–0.37 via water storage tank relocations. The corresponding annual electricity that can be saved is 160–410 TJ, a 0.1–0.3% of the total annual electricity consumption in Hong Kong.

1. Introduction

High-rise housing development, a trend in densely populated cities around the world, increases water supply energy consumption. A study of pumping energy use in urban water supply systems showed that the average energy consumption in residential buildings equaled 45% of the total pumping energy needed to deliver water from the treatment plants to households [1].

In Hong Kong, a developed city on the hilly terrain with limited usable land for buildings, very tall buildings are a trend in recent developments. Indeed, many newly constructed government-funded residential buildings are over 40 storeys or over 100 m and the current average residential building height in the city is estimated to be 25.8 storeys [2]. The total annual water consumption is about 1200 Mm^3 $year^{-1}$ (i.e. the per capita daily consumption is 408 L day^{-1}), and it will grow to 1315 Mm^3 $year^{-1}$ by 2030 [3]. Correspondingly, water supply systems in buildings account for approximately 1.6% of the total city electricity use according to the expression below, where E_{pump} is the energy use for pumping a volumetric water demand v_{pump}, N_B (=25.8 storeys) is the average building height, constants 3.6 and 60 accounts for unit conversion, one indicates additional pump lift of one storey height over the building's topmost floor, and 1.2 is a lumped value for pump and motor efficiencies, pipe friction and building storey height respectively [1].

$$E_{pump} = 3.6 \times \frac{1.2(N_B + 1)v_{pump}}{60} \tag{1}$$

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 designed for distributing water through down feed pipes [4]. To minimize the problems of water leakage or damage in supply pipes and appliances caused by excessive water pressure on lower floors in low demand situations, proper working pressure limits (e.g. 100–450 kPa) can be maintained using pressure reducing valves (PRVs). PRVs with adjustable settings and screwed joints are commonly installed to maximize application flexibility.

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Nomenclature

A	area (m^2)
C	constant head pressure
E	energy (MJ)
E_a, E_d	annual energy (MJ $year^{-1}$), daily energy (MJ day^{-1})
g	gravity (=9.81 ms^{-2})
H	pressure head of water column (m of H_2O)
h	height (m)
i, j	building floor counts, $i, j = 1, 2, \ldots, n$
N	number count
O	occupant area ratio (ps m^{-2})
V	volume (m^3)
v	volumetric water demand over a specified period (m^3)
α	energy efficiency
η_c	overall transmission efficiency
η_e	electric motor efficiency
η_m	mechanical transmission efficiency
η_p	pump efficiency
ϑ	random number between 0 and 1
ρ	water density (=1000 kg m^{-3})

Subscript

0	of reference
$1, 2, \ldots, n$	of demands $1, 2, \ldots, n$, from the bottom floor to the top floor
I, II	of cases I and II
a	of annually
B	of building storey
b	of water tank base
c	of water tank base to inlet
d	of daily
f	of friction in upfeed water pipe
ff	of floor to floor
L	of lower zone
l	of water lift
o	of outlet
out	of output
$pump$	of water pump
s	of occupant
U	of upper zone
%	of percentage

Superscript

$\sim$	of distribution
$*$	of relative
‘	of improvement

Although energy efficiency is a major concern for sustainable high-rise developments, there is no existing measure that systematically addresses the issue with respect to the optimal design and operation of high-rise water supply systems. Design solutions which integrate effective energy use into water planning process should be developed so as to save energy, reduce waste and protect our environment [5,6]. This paper proposes an energy efficiency evaluation measure for water supply system designs in buildings. Verification measurements in some high-rise residential buildings of Hong Kong are used to demonstrate the applicability of the evaluation model. Energy performance targets for some system designs, together with estimated energy savings potential are also derived.

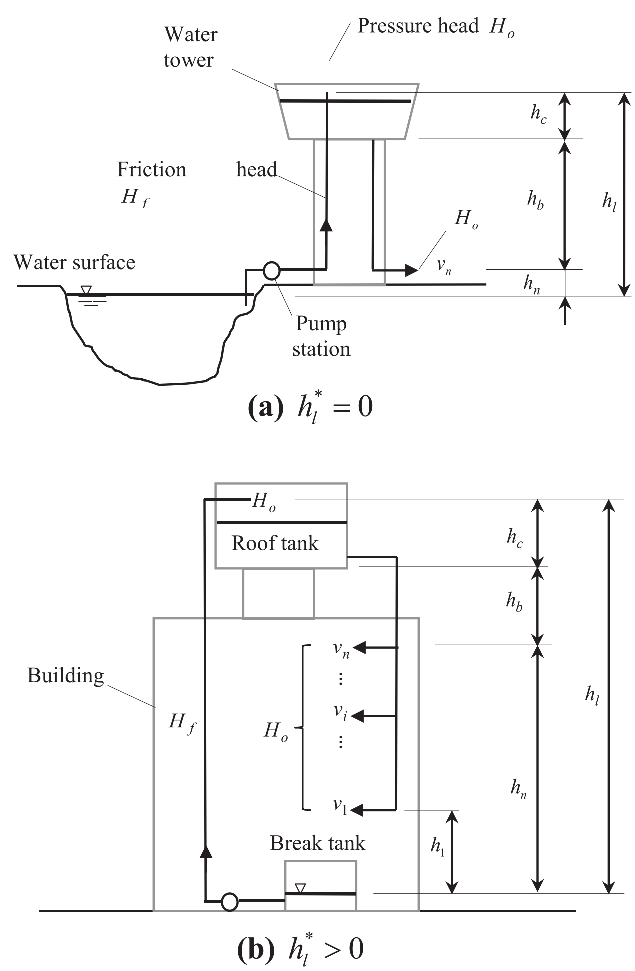

Fig. 1. Gravity tank systems.

2. Energy efficiency of building water supply systems

Water supply by an elevated reservoir over a town is used in practice. This idea has been commonly adopted in buildings by locating a roof tank. However, the two systems are not identical in terms of energy efficiency. Fig. 1 illustrates these two water supply system designs: (a) an elevated water tank that feeds demands with little height differences (e.g. an elevated water tower over a town); (b) a roof tank that feeds distributed demands with large height differences (e.g. a roof tank on top of a building). For a high-rise building, the system design is characterized by the water lift demand height ratio h_l^* given by Eq. (2), where $(h_n - h_1)$ is the height difference between the demands at the top and bottom for demand height $i = 1, 2, \ldots, n$ and h_l is the water lift height.

$$h_l^* = \frac{h_n - h_1}{h_l} \tag{2}$$

The water lift height h_l is the sum of the height measured from the tank base to the tank inlet h_c – approximated by the tank volume V_c, the height difference between the demand n and the tank base h_b, and the height difference between the water surface (i.e. of the reservoir in design (a) or of the break tank in design (b)) and the top demand location h_n,