Optimizing water supply pump replacement in buildings of Hong Kong

LT Wong , Y Zhou, KW Mui and CP Lau

Abstract

This paper investigates the pump efficiency of existing water supply systems in high-rise buildings in Hong Kong and provides economic justification for pump replacement by comparing the long-term energy cost savings to the initial installation costs. Energy consumptions of water supply pumps were measured with the pump efficiencies determined from the water consumptions of twenty water supply systems in buildings. The study results indicate that for typical pump motor ratings that range from 1 to 40 kW in a high-rise water system, with new pump efficiencies and annual pump efficiency drops that range from 0.68 to 0.74 and 0.012 to 0.028 respectively, a shorter replacement period can be justified on energy cost grounds for larger pumps with greater annual efficiency drops.

Practical application

This paper exhibits numerical solutions of replacement period justified on energy cost grounds for typical pump motor ratings that range from 1 to 40 kW in a high-rise water system, with new pump efficiencies and annual pump efficiency drops that range from 0.68 to 0.74 and 0.012 to 0.028 respectively.

Keywords

Energy cost, high-rise buildings, replacement schedule, water supply pump

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Nomenclature

ϑ	total cost (HKD$)
α	energy efficiency
η	pump efficiency
τ	time period (years)
θ_0	basic installation cost of a pump (HKD$)
θ_e, θ_m	pump annual energy cost (HKD$ year^{-1}) and replacement cost (HKD$)
ρ	water density (=1000 kg m^{-3})
C	coefficient (as defined in Equations)
E_s	daily energy consumption (kWh d^{-1})
E_m, E_o	water pumping system input and output energy (MJ)
g	gravity (=9.81 ms^{-2})
H_o, H_f	head pressures of water column of outlet and of friction in an upfeed water pipe (m of H_2O)
h	height (m)
I	line current (A)
K	ratio
P	pressure (Pa)
p	statistic *p*-value of the specified test
t	years of service (years)
V	line voltage (V)
v	volumetric water demand (m^3)
W_m	pump motor rating (kW)

Superscript

'	of yearly drop (year^{-1})

Subscript

0	of initial condition
1,2	of conditions 1, 2
η	of efficiency ratio
c	of cost per unit energy (HKD$ kWh^{-1})
e	of energy cost (HKD$)
j	of building floor j (=1,2,…,n, from the bottom floor to the top floor)
l	of water lift
m	of pump
p	of payback
r	of replacement
t	of t-th year condition

Introduction

Improving water-energy efficiency in buildings is a strategy to reduce carbon emissions nowadays.[1] The existing water supply system consumes 1-4% of electricity and is often a city's largest single electricity consumer. In fact, specific energy consumption plays an important role in the urban water cycle:[2,3] the specific energy use in Australia is 4.69 kWh/m^3, in California is 4.44 kWh/m^3, in Canada is 1.77 kWh/m^3; and it is 1.1-1.4 kWh/m^3 in some Asian cities.[4,5]

Energy consumption in water pumping system is proportional to building height. In order to deliver water from ground level to user appliances in the building, energy input to water is lost in the pumping system, except the potential energy available at the points of utilization.[5] Water pump efficiency indeed is not high (in a range around 0.5) and drops in its service life.[6] Therefore, how to maintain the efficiency of in-use water supply pumps in a dense, high-rise environment such as Hong Kong is a main concern. The greater the pump efficiency, the lower the pumping costs. Optimal performance of the pumping system can only be achieved with the proper design, selection, installation, maintenance and replacement of the pumps.

This paper evaluates the cost-benefit of pump replacement against pump efficiency drops in a typical water supply system life cycle for buildings in Hong Kong. Pump deterioration as well as replacement are studied and a pump replacement schedule justified on energy cost grounds is proposed.

Pump efficiency, replacement and payback period

For gravity-fed water supply systems in buildings, see Figure 1, the pump efficiency η is calculated by the total energy for lifting water from ground floor to roof tank divided by the power input to the pump motor as given below, where the (per one second) total pumped volume v_m (m^3), line current I_m (A) and line voltage V_m (V) of the pump motor over a pump operating period of τ_m=1 s can be measured on site,

$$\eta = \frac{P v_m / \tau_m}{\sqrt{3} V_m I_m} \tag{1}$$

The total pressure P (Pa) at the pump outlet is designed to overcome the pressure due to the desired minimum water pressure head available at the tank inlet H_o (m), the friction head required in the upfeed water pipe H_f (m), and the water lift height measured from the base of the water tank to the inlet of the roof tank h_l (m) as shown in equation (2), where ρ (=1000 kg m^{-3}) is the density of water and g (=9.81 ms^{-2}) is the gravity,

$$P = \rho g \left(H_o + H_f + h_l \right) \tag{2}$$

Energy efficiency α, a measure for an energy-efficient water supply system, is defined in equation (3), where E_m (MJ) is the pumping energy for lifting water to the roof tank and E_o (MJ) is the potential energy of the water supplied at the utilization point,

$$\alpha = \frac{E_o}{E_m}\,; \quad E_m = \frac{Pv_m}{\eta} \tag{3}$$

In the cases of non-uniformly distributed demands at levels j=1,2,…n, the potential energy E_o (MJ) is given by,

$$E_o = \rho g \sum_{j=1}^{n} v_j h_j \tag{4}$$

Equation (4) can be reduced for the cases of uniformly distributed demands along the building height as follows, where h_n (m) is the height difference between the water surface of the break tank (usually located on a lower floor) and the demand location on the top floor, and h_1 (m) is the demand location on the bottom floor (Figure 1),

$$E_o = \left(\frac{h_1 + h_n}{2}\right) \rho g \sum v_j \tag{5}$$

Pump performance deterioration is approximated by the annual drop in the overall pump efficiency η' (year^{-1}).[7] The overall pump efficiency η_t in the t-th year of service (years) is given by an expression below, where η_0 is the efficiency of the pump when new,

$$\eta_t = \eta_0 - \eta' \, t \tag{6}$$

The performance drop that increases with both t (years) and the pumping energy consumption can be reflected by the efficiency ratio K_η,

$$K_\eta = \frac{\eta_0}{\eta_t} \tag{7}$$

In providing economic justification for water pump replacement, the payback period τ_p (years) can be used as a method for making the decision. Figure 2 illustrates the relationship between time t (years) and cost ϑ. At time t_r (years), the beginning of the payback period, the pump replacement cost θ_m (HKD$) is expected to be recovered from the savings in energy and operating costs.

$$\vartheta_r(t):\ \begin{cases} \vartheta_r(0) = \theta_m \\ \vartheta_r(t_r) = \theta_m + \sum^{\tau_r} \theta_e \\ \vartheta_r(t_p) = \theta_m + \sum^{\tau_r + \tau_p} \theta_e \end{cases} \tag{8}$$

$$\vartheta_p(t):\ \begin{cases} \vartheta_p(t_r) = 2\theta_m + \sum^{\tau_r} \theta_e \\ \vartheta_p(t_p) = \vartheta_p(t_r) + \sum^{\tau_p} \theta_e \end{cases} \tag{9}$$

The payback period τ_p can be determined by solving for $\vartheta_r = \vartheta_p$ at t_p,

$$\theta_m + \sum^{\tau_r} \theta_e + \sum^{\tau_p} \theta_e - \sum^{\tau_r + \tau_p} \theta_e = 0 \tag{10}$$

Based on the typical pump motor ratings for water supply systems in buildings and the pricing data from public contracts, the pump replacement cost θ_m (HKD\$) is given by the following expression,[7] where θ_0 (HKD\$) is the basic installation cost of a pump and C_m (HKD\$ kW^{-1}) is the unit cost coefficient for the pump motor at rating W_m (kW),

$$\theta_m = \theta_0 + C_m W_m \tag{11}$$

Larger motor pump sets are generally installed to cope with the greater water demands for higher buildings with larger floor areas and populations. The daily energy consumption E_s (kWh d^{-1}) is assumed to be correlated with the pump motor rating W_m (kW), i.e. $E_s \sim W_m$. The annual energy cost θ_e (HKD\$ year^{-1}) in the t-th year is given by equation 12, where C_c (HKD\$ kWh^{-1}) is the unit energy cost (using the current price of HKD\$1 kWh^{-1}), $C_{e,0}$ and $C_{e,1}$ are the correlation constants,

$$\theta_e = K_\eta C_c E_s = K_\eta C_c C_{e,0} W_m^{C_{e,1}} \tag{12}$$

[insert Figure 1.]

[insert Figure 2.]

Survey study

The water pump efficiencies of 20 high-rise buildings (11 commercial, 4 residential, 3 school and 2 nursing home buildings) in Hong Kong were measured. In these buildings, gravity-fed systems were used for water distribution and pressure reducing valves were installed to control inlet pressure from the water mains supply. The pumps were all driven by 3-phase motors and their installation details, such as operation and maintenance manuals, number of years installed, installation costs, pump motor ratings, flow rates, pressures and water supply system schematic diagrams, were all studied. During the measurement period, pump operation data including the number of operations, start/stop times, and applied line currents and voltages were recorded. For each building, the total amount of water consumed in at least one week was registered.

Results and discussion

Table 1 summarizes the pump efficiencies of 20 building water supply systems in Hong Kong. α, the energy efficiency of a water supply system, is a measure of system performance and is influenced by the pump efficiency η.[5] A strong correlation between α and η was found in the measurement results (p<0.01, t-test). As shown in Figure 3, pump efficiency deteriorates over time; the values of η (ranged from 0.18 to 0.74) were correlated with the years of service t (p<0.05, t-test). The two trend lines in the figure indicate the pump efficiency drops resulted from the survey analysis for the best-case scenario (pumps with the lowest annual efficiency drop) and worst-case scenario (pumps with the highest annual efficiency drop) (i.e. η'=0.012 and 0.028 respectively per year of service). The average values of individual pump data distributed nearby in η-t coordinates were calculated, and the average efficiency drop was η'=0.015. By extending the results to t=0, the design efficiency of a new pump was approximated to be η_0=0.68-0.76. Linear efficiency drop is assumed and the analysis is reasonable over only small time increments.

Systems 14 and 15 were of identical designs but reported very different pump efficiencies, i.e. 0.52 and 0.74 respectively. Both systems were fed by end-suction pumps - the pumps used in System 14 were over 20 years old while those used in System 15 were 1 year old only - and their average efficiency drops were approximated by the best-case scenario line η'=0.012. Figure 3 shows that the overall pump efficiency of System 14 can be improved by pump replacement. Similarly, although Systems 1 and 2 were using the same pump type, they had different pump efficiencies (i.e. 0.18 vs. 0.39) as the pumps used in System 1 were 10 years older. The average efficiency drops of both Systems 1 and 2 were approximated by the worst-case scenario line η'=0.028. Among the 20 surveyed systems, the lowest pump efficiency was found in System 1.

[insert Figure 3.]

The pump motor ratings surveyed were found to be correlated with the total floor area (p<0.01, t-test), water delivery height (p<0.01, t-test) and population (p<0.01, t-test). The pumping energy consumption was found to be correlated with the motor ratings, with correlation constants $C_{e,0}$=1.232 and $C_{e,1}$=1.27. It was reported that the basic local pump replacement cost (θ_0) was HKD$3700 and the unit pump motor cost (C_m) was HKD$1780 kW^{-1}. The corresponding energy cost to pump replacement cost ratio $\theta_{e,0}/\theta_m$ (i.e. a parameter for determining the first pump replacement period and the payback period of a pump replacement) for a pump motor rating W_m in the range of 1-40 kW was in the range of 0.08-0.65. The constants for pumps used in building water supply systems in Hong Kong are summarized in Table 2.

Table 1. Pump efficiencies of 20 building water supply systems in Hong Kong

No.	[a]Type	Floor area (m^2)	Storey	Population (heads)	Years of service t (years)	Height h_l (m)	Average demand height $(h_1+h_n)/2$ (m)	[b]Pumped volume (m^3)	Pump daily energy E_s (kWh day^{-1})	Demand daily energy E_o (kWh)	Pump efficiency η	System efficiency α
1	C	1250	21	600	20	142	76	87	183	33.7	0.18	0.10
2	C	1250	1	600	10	142	140	105	104	40.6	0.39	0.38
3	C	750	24	1200	12	120	57.5	95	67	30.9	0.46	0.22
4	C	400	31	1378	5	138	76	132	81	49.8	0.62	0.34
5	C	300	30	1000	12	142	71	100	86	38.6	0.45	0.22
6	C	150	20	333	10	55	27	19	7	2.9	0.42	0.21
7	C	100	20	222	5	82	41	68	27	15.1	0.55	0.28
8	C	600	20	1333	11	90	45	60	39	14.8	0.38	0.19
9	C	200	16	356	15	68	34	35	18	6.4	0.36	0.18
10	C	300	12	400	16	53	26	40	16	5.7	0.36	0.18
11	C	800	20	1778	18	92	46	44	24	11.0	0.46	0.23
12	R	625	31	1085	20	114	54	685	434	212.9	0.49	0.23
13	R	625	31	1085	20	114	54	851	505	264.3	0.52	0.25
14	R	1080	35	2940	20	130	65	2084	1409	738.2	0.52	0.26
15	R	1080	35	2940	1	130	65	1851	882	655.7	0.74	0.37
16	S	400	6	1050	10	34	15	49	7	4.5	0.66	0.29
17	S	600	5	1000	18	42	19	68	14	7.8	0.55	0.25
18	S	500	2	300	8	18	7.5	53	6	2.6	0.46	0.19
19	N	600	4	400	10	20	8	390	40	21.3	0.53	0.21
20	N	600	4	400	4	21	9	[c]328	31	18.8	0.61	0.26

[a] Type: C=commercial; R=residential; S=school; N=nursing home; [b]7-day water consumption; [c]10-day water consumption.

Table 2. Constants for building water supply pumps in Hong Kong

Parameter	Values
η_0	0.68–0.76
η'	0.012–0.028
θ_0	3700 HKD
C_m	1780 HKD$ kW^{-1}
$C_{e,0}$	450
$C_{e,1}$	1.27
$\theta_{e,0}/\theta_m$	0.08–0.65
W_m	1–40 kW

Sensitivity of the ratio $\theta_{e,0}/\theta_m$ was evaluated with respect to the variations in energy and replacement costs. Figure 4 graphs the sensitivity results for: 1) halving/doubling the replacement cost θ_m; and 2) ±20% of the energy cost θ_e. As indicated in the figure, the cost ratio is more sensitive to energy cost for larger pumps (e.g. W_m>8 kW). Since pump performance deterioration leads to higher energy costs, it is a concern particularly for high-rise water system designs where larger pumps are employed.

[insert Figure 4.]

The best-, average- and worst-case scenarios of pump efficiency drops within a range of design efficiencies for a new pump (i.e. η_0=0.68-0.76) are graphed in Figure 5. According to the figure, the annual energy costs of a pump can increase by 120-160% and 40% in the worst- and average-case scenarios respectively after 15 years of service. Figure 5 also illustrates the significant effect of design efficiency on efficiency ratio. As the efficiency ratio differences for the best-, average- and worst-case scenarios of a 15-year-old pump can be up to 4%, 5% and 15% respectively, improvement in design efficiency can yield significant energy savings.

[insert Figure 5.]

[insert Figure 6.]

[insert Figure 7.]

Replacement periods for the first installation of a pump in the W_m range of 1-40 kW were examined and criteria could be set for a pump replacement justified on energy cost grounds. Figure 6 reveals the results of two example cases. Case (a) $\theta_m = \sum_{t=0}^{\tau_p} \theta_{e,t}$ indicates the period in which the installation cost equals the operation cost; and case (b) $\tau_r=\tau_p$ indicates that the cost for a pump replacement is justified by the extra energy cost. Taking an indicative pump life of 15 years (some local practice norms), Figure 6(a) shows that a shorter replacement period (e.g. $\tau_r \leq 10$ years) can be justified for larger pumps (e.g. $W_m \geq 10$ kW) at higher annual efficiency drops ($\eta' \geq 0.028$); for instance, $W_m \geq 10$ kW at $\eta' \geq 0.015$ and $W_m \geq 2$ kW at $\eta' \geq 0.028$. From Figure 6(b), the first replacement justification can be seen at $W_m \geq 2$ kW for the best- and average-case pump efficiency drop scenarios (i.e. η'=0.012 and 0.015), and at W_m=1–40 kW for the worst-case scenarios (i.e. η'=0.028).

Figure 7 highlights the two example cases in terms of payback periods for the first replacement periods of τ_r=10 and 15 years. The replacement period can be justified by a shorter payback period before further replacement. Figure 7 also demonstrates that all cases can be justified by the use of payback period if an indicative pump life of 15 years is adopted, except for W_m<3kW at η' <0.015 and W_m<4kW at η' <0.012 where payback periods are longer than 15 years. It is observed that larger pumps and higher efficiency drops justify a shorter replacement period.

The results of replacement and payback periods are summed up in Table 3; examples of pump motor ratings for 5, 10, 20 and 40 kW are shown for easy reference. When a practical replacement can be arranged, more frequent replacements are highly justified.

Table 3. Example replacement and payback periods

Pump motor rating W_m (kW)	**Annual efficiency drop**					
	η'=0.012	**η'=0.015**	**η'=0.028**	**η'=0.012**	**η'=0.015**	**η'=0.028**
	Replacement period τ_r (years) at (a) $\theta_m = \sum_{t=0}^{\tau_p} \theta_{e,t}$			**Replacement period τ_r (years) at (b) $\tau_r=\tau_p$**		
5	13.4	10.2	4.2	8.8	6.5	2.1
10	10.2	7.8	3.2	6.6	4.8	1.5
20	8.1	6.2	2.5	5.1	3.8	1.2
40	6.6	5.0	2.0	4.2	3.0	1.0
	Payback period at τ_r=10			**Payback period at τ_r=15**		
5	18.7	16.5	11.4	11.6	10.1	6.7
10	16.1	14.2	10.0	10.1	8.8	5.9
20	14.3	12.6	8.9	9	7.9	5.4
40	12.9	11.4	8.1	8.2	7.2	4.9

Conclusion

Improving energy efficiency in buildings is a sustainable development strategy in Hong Kong. It is necessary to develop a more integrated approach to energy efficiency in high-rise water systems. This paper examined 20 building water supply systems in Hong Kong and proposed a pump replacement schedule with justification by comparing the long-term energy cost savings to the initial installation costs. The study results demonstrated that for typical pump motor ratings that range from 1 to 40 kW in a high-rise water system, with new pump efficiencies and annual pump efficiency drops that range from 0.68 to 0.74 and 0.012 to 0.028 respectively, a shorter replacement period can be justified on energy cost grounds for larger pumps with greater annual efficiency drops.

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References

1. Shimizu Y, Toyosada K, Yoshitaka M, Sakaue K. Creation of Carbon Credits by Water Saving. *Water* 2012; 4: 533–544.
2. Plappally AK, Lienhard JH. Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews* 2012; 16(7): 4814–4848.
3. Rio CAM, Frei C. Water: A key resource in energy production. *Energy Policy* 2009; 37: 4303–4312.
4. Cheng CL. Study of the inter-relationship between water use and energy conservation for a building. *Energy and Buildings* 2002; 34(3): 261-266.
5. Cheung CT, Mui KW, Wong LT. Energy efficiency of elevated water supply tanks for high-rise buildings. *Applied Energy* 2013; 103: 685–691.
6. Kaya D, Yagmur EA, Yigit KS, Kilic FC, Eren AS, Celik C. Energy efficiency in pumps. *Energy Conversion and Management* 2008; 49:1662–1673.
7. Wong LT, Mui KW, Lau CP, Zhou Y. Pump efficiency of water supply systems in buildings of Hong Kong. *Energy Procedia* 2014; 61: 335–338.

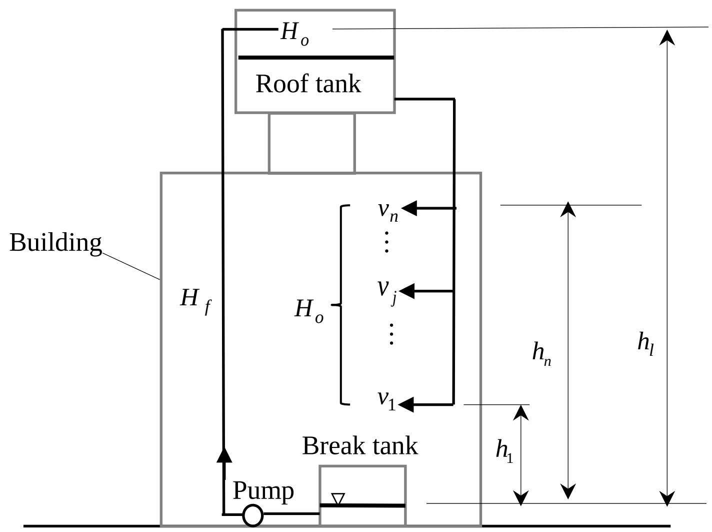

Figure 1. Gravity-fed water supply systems

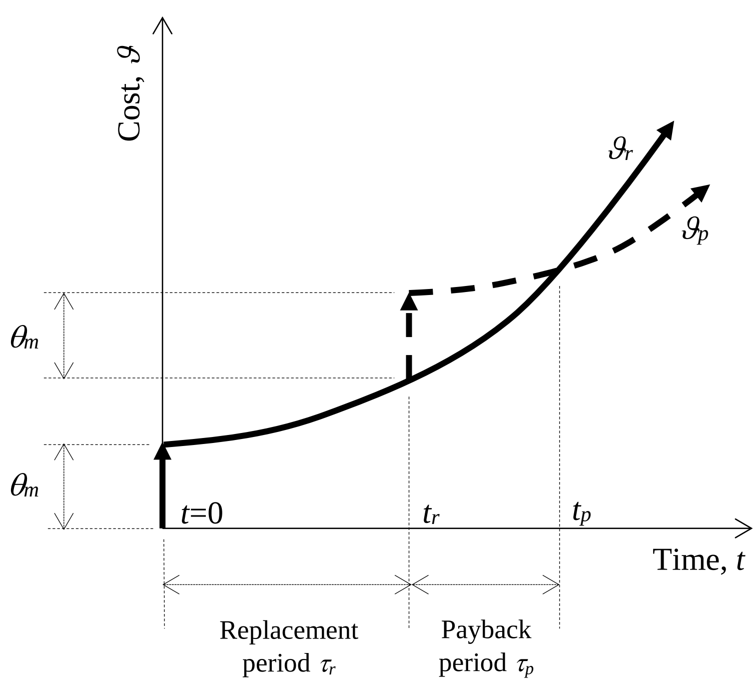

Figure 2. Replacement and payback periods

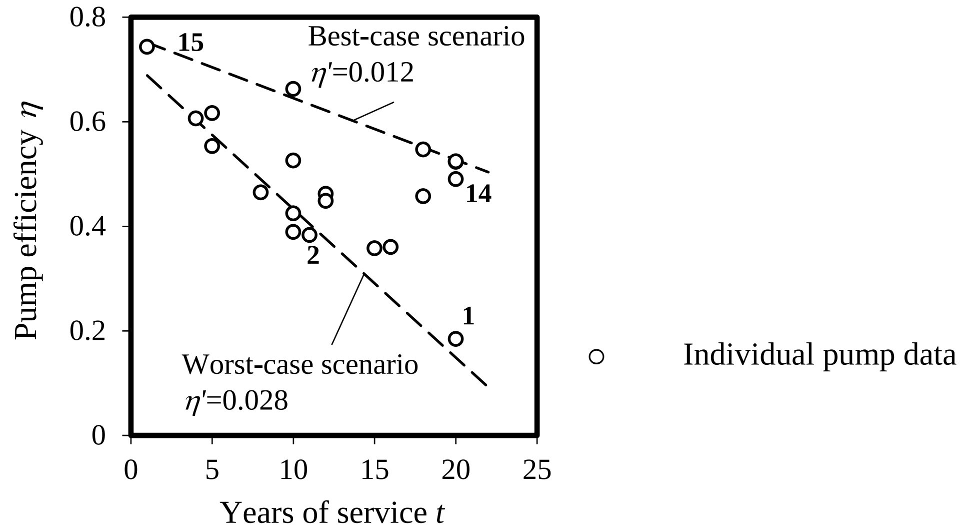

Figure 3. Pump efficiencies of 20 water supply systems in buildings

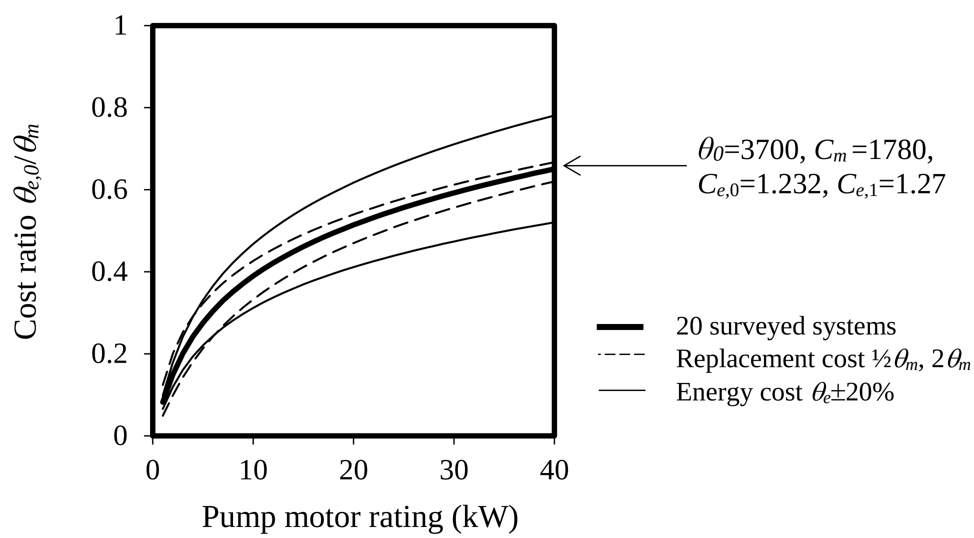

Figure 4. Cost ratio of a pump replacement

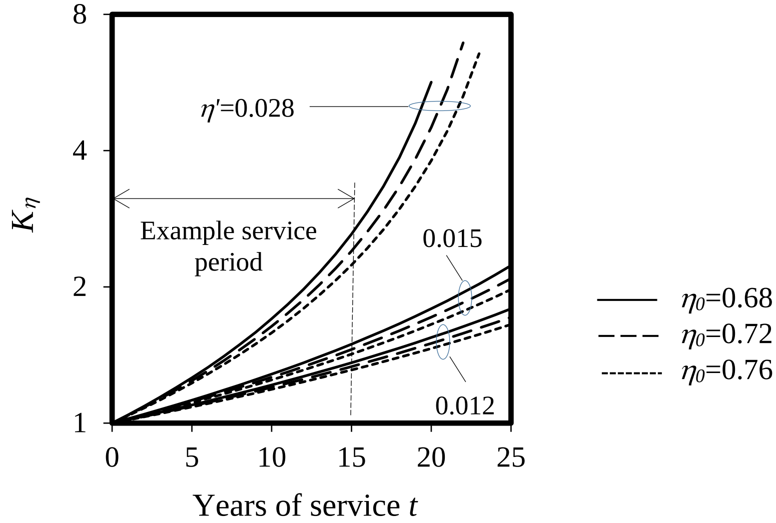

Figure 5. Efficiency ratio K_η against years of service t of a pump

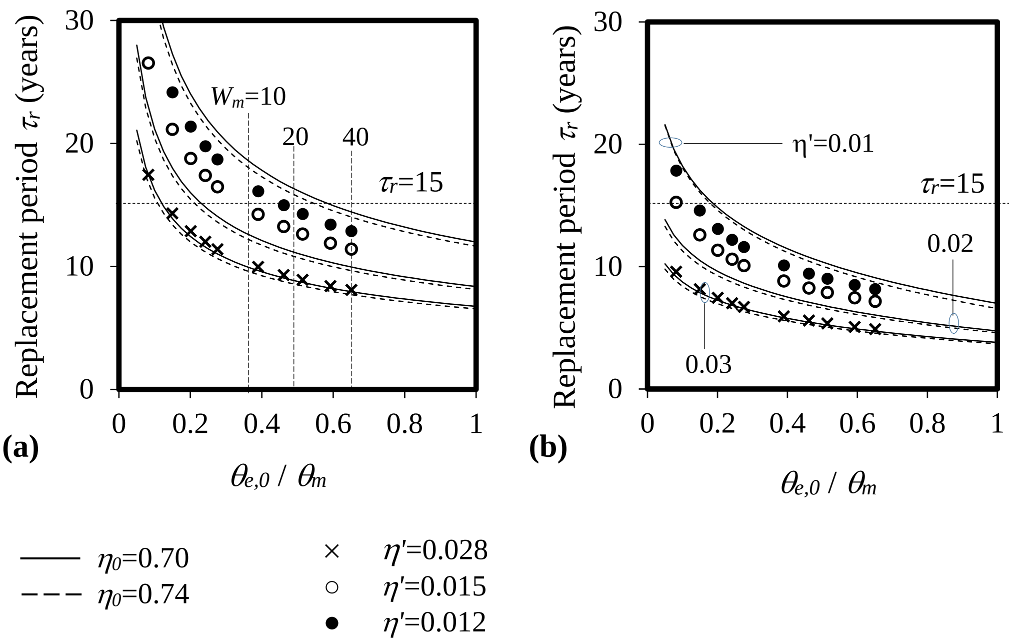

Figure 6. Replacement periods τ_r at: (a) $\theta_m = \sum_{t=0}^{\tau_p} \theta_{e,t}$; and (b) $\tau_r = \tau_p$

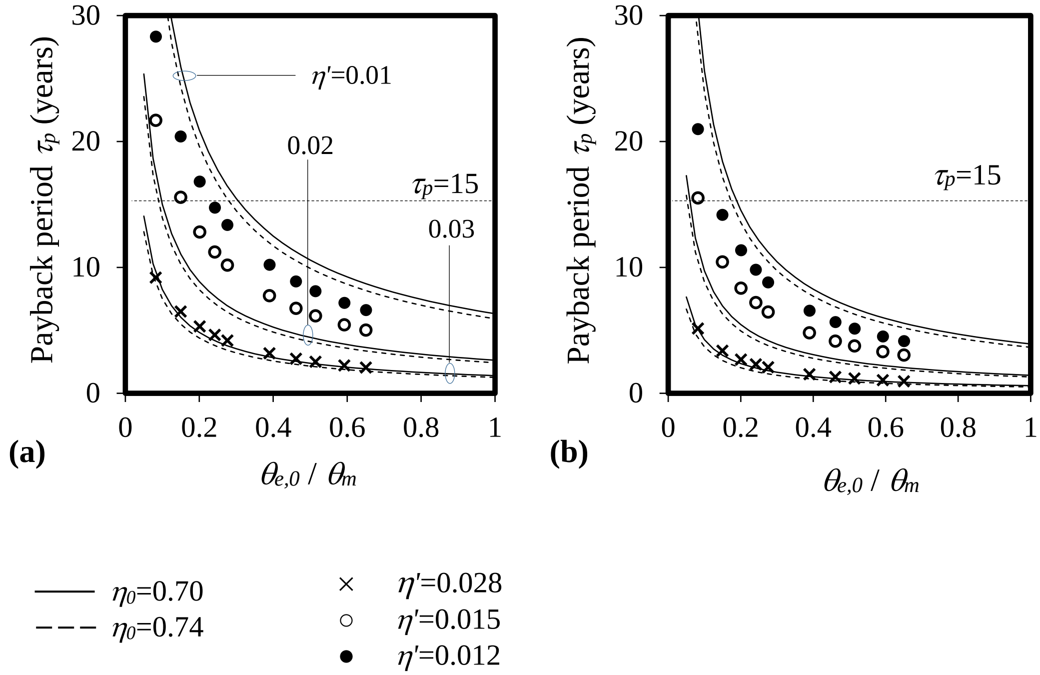

Figure 7. Payback periods τ_p at: (a) τ_r=10; and (b) τ_r=15