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Shower water heat recovery in high-rise residential buildings of Hong Kong

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(Summary) This paper investigates the potential for shower water heat recovery from bathrooms equipped with instantaneous water heaters in high-rise residential buildings of Hong Kong.

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Abstract

This paper investigates the potential for shower water heat recovery from bathrooms equipped with instantaneous water heaters in high-rise residential buildings of Hong Kong. A simple single-pass counter-flow heat exchanger installed horizontally beneath the shower drain is employed as a localized heat recovery measure for preheating cold water going to a water heater. The thermal energy exchange is evaluated using the effectiveness-number of transfer units (ε-NTU) approach. Shower usage patterns including shower operating time and water flow rate sampled from an interview survey via the Monte Carlo sampling technique, together with the water temperatures at the shower heads, shower drains and cold water supply mains recorded in sample shower operations, are the input parameters. The results indicate that 4-15% shower water heat can be recovered through a 1.5 m long single-pass counter-flow heat exchanger for a drainage pipe of diameter 50 mm.

Keywords: hot water shower; waste heat recovery; residential buildings

1. Introduction

Statistics showed that residential buildings consume 17% of the total energy of Hong Kong [1]. Reduction of the energy consumption in residential buildings is a key area of any strategy to energy conservation programme. Scenarios of the potential for residential energy conservation including the improvement on external wall insulation, weatherproofing of openings, installation of double glazed windows/external shading system, better maintenance of boiler regulators, control upgrades for a heating and cooling system, and installation of solar sanitary hot water production unit were investigated [2]. As the breakdown of energy consumption in residences showed that 20% of the energy was for the production of hot water of which a large portion was used for personal hygiene such as bathing or showering, a truly efficient domestic hot water system can optimize energy savings.

Progress has been made in the past decades that technology and equipment support energy saving for hot water systems in residential buildings, such as solar collectors, heat pump, co-generation system and heat recovery system. Installation of solar collectors in apartment buildings can conserve 60% to 74% of the energy mainly depending on the building's location and climatic conditions in Greece [3]. In Hong Kong, the potential application of a centralized solar water heating system for a high-rise residential building was evaluated based on local meteorological data. It was found that the annual efficiency of a vertical solar collector could reach an average of 38%, giving a solar fraction of 53% and a payback period of 9 years for those apartments where installation was feasible [4]. Nevertheless, the position of a solar panel is critical especially in a high-rise high-density environment to cost justify the installation.

Individual energy conservation equipment in the residential sector (e.g. micro-cogeneration system, water tank regulator, desuperheater, heat pump water heater indirectly coupled to a space conditioning, etc.) has the ability to produce useful thermal energy and electricity from a single fuel source and thus provides for uncomplicated efficiency improvement potential [5,6]. A recent survey of domestic water appliances reported that private instantaneous water heaters were commonly found in domestic washrooms in Hong Kong [7,8]. Localized installations were chosen over a centralized system due to the ease of energy cost metering as well as the simplicity of appliance ownership, installation, operation and maintenance [9,10]. Moreover, an instantaneous water heater is compact in size with reasonable energetic efficiency [11].

The most commonly used type of heat recovery system is the shell-and-tube heat exchanger. The primary objective of its design is the estimation of the minimum heat transfer area required for a given duty, as it governs the overall cost of the heat exchanger. There are lots of heat transfer enhancement techniques for heat exchangers, such as increasing of the heat transfer area, enhancing of the turbulence, reducing of the boundary layer thickness, generating of the secondary flow, changing of the flow velocity and temperature gradients were investigated [12]. However there is no concrete function that can be expressed explicitly as a function of design variables and in fact many numbers of discrete combinations of the design variables are possible [13]. These heat exchanger optimization design problems with multiple design variables such as outer tube diameter, tube layout, number of tube passes, outer shell diameter, baffle spacing and baffle cut were solved with genetic algorithm and the field synergy number maximization approach was formulated. An optimum design leads to a significant cost cut on the one hand and an improvement of the heat exchanger performance on the other hand [14]. Furthermore, the investment and the annual energy expenditures related to the components were also discussed [15]. Various modeling approaches were examined in describing the energy for hot water consumption records in residential buildings [16,17]. However, the energy savings potential for localized waste heat recovery systems in high-rise residential buildings has not been deeply developed [18]. This study investigates such potential via Monte Carlo simulations using waste streams from domestic shower drains.

2. Waste heat recovery

A localized wastewater heat recovery system can recapture heat from the shower drainage and serve as the first stage of heat recovery and extraction in a central heating plant. Figure 1 shows a typical shower installation for high-rise residential buildings in Hong Kong with a simple single-pass counter-flow heat exchanger horizontally installed beneath the shower drain. The heat exchanger, a localized shower water heat recovery measure, preheats cold water going to the water heater.

Transmission heat loss along a long hot water pipe is a significant factor in designing the waste heat recovery system in a high-rise building [19]. However, for a preliminary demonstration, this study assumed no heat loss and short pipe length for a drainage pipe collecting hot water from a shower. The assumption is justified with practical installation space available and arrangement in typical bathroom facilities of high-rise residential apartment buildings in a high-dense built environment. A survey showed that the slope drainage pipe length was about 1m to 1.5m long [20]. With the heat exchanger configuration shown in Figure 1 that the slope drainage pipe running in a cold water supply pipe, the temperature difference between the preheated water and ambient is not expected high.

Calculations below emphasize on the waste heat recovery system performance and the minimum energy consumption of a water heater is determined as a reference case for discussion of the feasibility and applicability in high-rise apartment buildings. Hence, for the water heater to heat up the cold water supply to the shower head water temperature T_2 (ºC), the power consumptions without the heat exchanger $\dot{Q}_0$ (kW) and with the heat exchanger installed $\dot{Q}_1$ (kW) would be as expressed below, where T_0 (ºC) is the cold water supply temperature, T_1 (ºC) is the preheated water temperature, c_p (kJ kg^{-1} ºC^{-1}) is the specific heat capacity and m_c (kg s^{-1}) is the mass flow rate of cold water supply entering the heat exchanger,

$$\begin{cases} \dot{Q}_0 = m_c c_p \left(T_2 - T_0\right) \\ \dot{Q}_1 = m_c c_p \left(T_2 - T_1\right) \end{cases} \tag{1}$$

The annual energy saving ΔE (kWh yr^{-1}) for a shower operation due to the heat recovery measure is computed by Equation (2), where τ (s yr^{-1}) is the annual shower operating time, E_0 (kWh yr^{-1}) is the annual water heater energy consumption without the heat exchanger and E_1 (kWh yr^{-1}) is the annual water heater energy consumption with the heat exchanger installed,

$$\Delta E = E_0 - E_1 = \int_\tau \dot{Q}_0(t)dt - \int_\tau \dot{Q}_1(t)dt \tag{2}$$

Effectiveness of the heat exchanger depends on the overall heat transfer coefficient U_o (kW m^{-2} ºC^{-1}) and the heat transfer area A_o (m^2). Because of insignificant heat loss and pipe length, T_1 (ºC) can be evaluated via the effectiveness-number of transfer units (ε-NTU) approach [21],

$$T_1 = T_0 + \frac{\dot{Q}}{\dot{C}_{min}}; \ \dot{Q} = \varepsilon \dot{C}_{min}\left(T_3 - T_0\right); \ \varepsilon = \frac{1 - \exp\left[-NTU\left(1 - C_r\right)\right]}{1 - C_r \exp\left[-NTU\left(1 - C_r\right)\right]}; \ NTU = \frac{U_o A_o}{\dot{C}_{min}} \tag{3}$$

where, $\dot{Q}$ (kW) is the actual heat transfer rate, ε is the heat exchanger effectiveness, T_3 (ºC) is the drain water temperature, NTU is the number of transfer units, C_r is the capacitance ratio, $\dot{C}_c$ (kW °C^{-1}) and $\dot{C}_h$ (kW °C^{-1}) are the heat capacitance rates, $\dot{C}_{min}$ (kW °C^{-1}) and $\dot{C}_{max}$ (kW °C^{-1}) are the minimum and the maximum heat capacitance rates respectively determined by,

$$C_r = \frac{\dot{C}_{min}}{\dot{C}_{max}}; \ \begin{cases} \dot{C}_{min} = \min\left(\dot{C}_c, \dot{C}_h\right) \\ \dot{C}_{max} = \max\left(\dot{C}_c, \dot{C}_h\right) \end{cases}; \ \begin{cases} \dot{C}_c = m_c c_p \\ \dot{C}_h = m_h c_p \end{cases} \tag{4}$$

where, m_h (kg s^{-1}) is the mass flow rate of hot water supply entering the heat exchanger.

3. Shower usage patterns

The shower usage patterns were retrieved from an earlier survey study [20]. In the survey, a total of 1,300 households were randomly picked from 14 typical high-rise residential buildings among 5 housing estates in Hong Kong. Those 5 estates provided 26,500 apartments for a population of 113,000. The buildings were selected based on various geometrical locations, building ages and architectural designs for the study of appliance usage patterns in domestic washrooms. Invitation letters were sent through the estate management offices to introduce the study objectives, the survey period and other details. Data were collected from representatives of the 597 responded households through face-to-face interviews. Most of the interviewees were occupants who stayed at home for the longest time every day. During the interviews, they were asked to provide information of the appliance usage patterns on the day prior to the interview, and the hourly usage patterns on weekdays, weekends and holidays. The average time between appliance demands was also surveyed. For each installed appliance, the type, physical size, brand name, usage frequency and water flow rate were recorded.

The survey reported that an occupant took at least one shower everyday; 269, 289, 37 and 2 interviewees would take 1, 2, 3 and 4 showers in a summer day but 537, 57, 3 and none would take 1, 2, 3 and 4 showers in a winter day. It was also reported that all the winter showers and 97% summer shower were hot water ones, which the hot water heater was operated. According to Figure 2, an occupant would take N_s=1.6 (standard deviation or SD=0.6) showers on a summer day (Jun to Aug) and 1.1 (SD=0.3) showers on a winter day (Dec to Feb), giving an overall average of 1.4 (SD=0.6) showers per day. The distribution function of average pattern was used for the rest of a year (i.e. Sep to Nov and March to May) in the subsequent calculation in this paper. It is noted that the average value was significantly higher than the average value of N_s=0.4 $hd^{-1}d^{-1}$ (ranged from 0.07 to 0.7 $hd^{-1}d^{-1}$) surveyed in other cities (p<0.01, t-test) [22,23]. Figure 3 displays the discharge time of a shower operation recorded. The geometric average was 12 minutes with a geometric SD of 1.6 minutes.

4. Temperature measurements

A total of 3 volunteers (a male adult, a female adult and a child) were invited to take showers in a high-rise residential apartment with 2 typical washrooms for 4 weeks in a year, i.e. one week each in Jan, Apr, Jul and Oct of a year. Although the volunteers were local residents and the sample cases were assumed typical, future measurements with statistical techniques for small sample size (e.g. Bayesian approach [24]) would improve the confidence levels of parameters of occupant average choices. The test facility installed with a shower head 2 m above the shower drain at the floor level. The hot water supply at the shower head was from a water supply main and heated up by a metered fuel-gas water heater. It was noted that water supply pipes in high-rise residential buildings were normally enclosed indoor or embedded in the building structure. No heat loss through evaporation was expected. The shower times were 18:00-01:00 and 06:00-09:00. Water temperatures at the water supply mains, shower heads and shower drains were measured by thermocouples and logged in a personal computer in a recording time interval of 5 seconds for all shower operations, during which the outdoor air dry-bulb temperature ranged from 13ºC to 28ºC, measured outside the washroom. It covers typical ambient temperature range of showering time as shown in Figure 5. It was found that the measured cold water supply temperature was higher than the outdoor air dry-bulb temperature at $T_a \leq 27$ °C (p<0.01, t-test) but was lower than that at $T_a \geq 28$°C . Properly, the embedded water supply pipe temperatures were affected by the thermal mass of the building structure. A significant correlation was observed between outdoor temperature T_a (°C) and the water supply temperature T_0 (°C) (Correlation coefficient R=0.97, $p \leq 0.01$, t-test),

$$T_0 = 10.4 T_a^{0.29}; \; 13 \leq T_a \leq 28 \tag{5}$$

It was reported that water temperature observed at the shower head T_2 (ºC) stayed relatively constant with an average of 40.9ºC (SD=1.0ºC). It dropped down to T_3 (ºC) at the shower drain in all observations. The temperature drops between the shower head and shower drain $\Delta T_{2,3}$ would be correlated with the shower head water temperature and the outdoor air temperature T_a (ºC) as follows (R=0.78, $p \leq 0.01$, t-test),

$$\Delta T_{2,3} = T_2 - T_3 = 3.6 \times 10^{-10} T_2^{6.673} T_a^{-0.530} \tag{6}$$

Figure 4 shows the measured temperature drops against the calculated ones by Equation (6). The standard error is 0.88°C.

Based on the air temperature variations recorded in Hong Kong purchased from the Hong Kong Observatory, monthly profiles of the outdoor air temperature in years 1884-2006, the cold water supply temperature, and the shower temperature drop were determined for all shower operations. These profiles are exhibited in Figure 5 for subsequent evaluations.

5. Heat exchanger effectiveness

Design values of effectiveness- number of transfer units available in literature would not be directly applicable because a slope drainage pipe is only partially filled with hot water. A full-scale experimental setup was used to calculate the deficiency of the effectiveness ε of a single-pass counter-flow heat exchanger. As depicted in Figure 6, the horizontally installed heat exchanger is a 1 m long cold water PVC pipe (0.1 m in diameter) with a hot water copper pipe (40 mm in diameter) passing through it. The hot water copper pipe which simulates a slope drainage pipe is partially filled with hot water. It was noted that gravity water flows in partially filled slope drainage pipes can be described by fundamental fluid flow principles [25]. Apart from the time very beginning of the showering period and the location close to the drain entrance, the water flow in a horizontal (branch) pipe can be considered as steady and uniform, i.e. no changes with time, and the pipes remain of the same diameter and at the same slope over the length over which the Chezy equation is applied [26]. The partially filled steady flow pattern was observed in the experiments. In the experiment, in brief, any cold water entering the lower part of the heat exchanger at position (a) will be heated up by the drainage pipe.

Experiments for a range of NTU were conducted using pipes at gradients 1/500, 1/250, 1/200, 1/125, 1/67, 1/40, and testing conditions of hot water temperatures from 38°C to 40°C, and cold water temperatures from 14°C to 16°C. During the experiments, temperatures T_0 (°C), T_1 (°C), T_3 (°C) and T_4 (°C) were measured by K-type thermocouples at locations (a), (b), (c) and (d) respectively. The cold water temperature T_0 (°C) was measured at a discharging washbasin tap during the shower operation. Water flow rates to and from the pipes were also measured. It was noted that the NTU of the experimental conditions was determined by Equation (3) and plotted against the measured average heat exchanger effectiveness ε, which can be evaluated from the following expressions as described in Section 2 [21],

$$\varepsilon = \frac{\dot{Q}}{\dot{C}_{min}(T_3 - T_0)};\ \dot{Q} = \dot{C}_{min}(T_1 - T_0);\ \dot{C}_{min} = \min(\dot{C}_c, \dot{C}_h);\ \begin{cases} \dot{C}_c = m_c c_p \\ \dot{C}_h = m_h c_p \end{cases} \quad (7)$$

No significant difference was found among the effectiveness values for the slopes tested (p>0.1, t-test). Figure 7 presents the heat exchanger effectiveness as a function of NTU, showing alongside for comparison is the data of a similar heat exchanger with a drainage pipe fully filled with hot water [21]. The heat capacity of water, which is higher in a long and thick pipe than in a short and thin one, is dependent on the water volume. As expected, the heat exchanger tested in this study (i.e. partially filled with hot water) was less effective. A drop in average effectiveness observed was 8% with a standard error of 1.2% and the following expression was used in determining the potential energy saving,

$$\varepsilon = 0.92 \times \frac{1 - \exp\left[-NTU\left(1 - C_r\right)\right]}{1 - C_r \exp\left[-NTU\left(1 - C_r\right)\right]} \quad (7)$$

6. Potential energy savings

The estimates of the energy consumptions required to compute the saving potential are complex functions of the parameters, the Monte-Carlo simulations can be used to obtain confidence intervals for such estimates [27]. Energy savings potential for the heat exchanger was therefore evaluated via Monte Carlo simulations. Input parameters ζ_i (dummy variables), including the surveyed water temperatures as shown in Figure 5, number of shower operations per person per day in Figure 2 and shower duration in Figure 3, were sampled from the distribution functions $\tilde{\zeta}_i$ for typical Hong Kong domestic washrooms [28]. The simulation procedure process was as follows. A random number $x \in [0,1]$ was taken from a random number set, which was generated by the prime modulus multiplicative linear congruential generator [29]. It was noted that this random number set was tested and applied in a number of engineering applications [30-33]. Input value $\zeta_{i,x}$ of each parameter ζ_i was determined from the descriptive distribution function $\tilde{\zeta}_i$ at the percentile x,

$$\zeta_i = \zeta_{i,x}\,;\ \int_{-\infty}^{\zeta_{i,x}} \tilde{\zeta}_i \, d\zeta_i = x\,;\ \zeta_i \in \tilde{\zeta}_i \quad (9)$$

For a shower facility with a typical slope drainage pipe of diameter 0.04 to 0.05 m and length 0.6 to 1.5 m, the annual energy saving S (%) was determined for each simulation run using Equation (10), where j is the number of shower operations taken by an occupant at the shower, E_0 (kWh yr^{-1}) is the annual energy consumption without the heat exchanger, and E_1 (kWh yr^{-1}) is the annual energy consumption with the heat exchanger installed,

$$S = \frac{\sum E_{0,j} - \sum E_{1,j}}{\sum E_{0,j}} \tag{10}$$

For each case, the likelihood function for S (%) was determined from 25,000 repeated simple Monte Carlo simulations (SMS) [34]. It was noted that the average simulated values of each input parameter $\bar{\zeta}_i$ was less than 1% error compared with the expected value of the descriptive distribution function $<\tilde{\zeta}_i>$,

$$\left| \frac{\bar{\zeta}_i - \langle \tilde{\zeta}_i \rangle}{\langle \tilde{\zeta}_i \rangle} \right| \leq 0.01 \tag{11}$$

Figure 8 shows the expected annual energy savings <S> (%) for a single-pass counter-flow heat exchanger installed below the slope drainage pipe with a standard error <<S>> approximated by (R=0.9984, p <0.0001, t-test),

$$<< S >> = 0.052 < S >^{0.89} \tag{12}$$

The simulation outcome was used to quantify the potential energy savings through localized shower water heat recovery systems for a typical high-rise residential building [16]. The chosen building, 40 floors in height, had 20 apartments per floor and a total number of 800 showers installed. With a design population of 3,500 and a total floor area of 41,500 m^2, its occupant-area ratio was 0.084 person m^{-2} (SD=0.032 person m^{-2}); and its expected occupant load was 3,486 persons. The entire duration of shower operations was surveyed, and the corresponding outdoor temperature range reported was similar to the input parameter range selected in this study. For illustration, two heat exchanger specifications (or the worst- and best-case scenarios for practical installation) were considered in terms of the overall heat transfer coefficient U_o (kW m^{-2} ºC^{-1}), shower drainage pipe diameter D (m) and length L (m), i.e. (U_o, D, L) = [(300, 0.04, 0.6), (450, 0.05, 1.5)]. The simulations showed that the expected annual thermal energy consumption for hot water showers was 60.7 kWh m^{-2} yr^{-1} (SD=13.3 kWh m^{-2} yr^{-1},). According to the performance data in Figure 8, the total annual thermal energy savings expected for this sample building would be from 104 MWh yr^{-1} (SD=21 MWh yr^{-1}) to 406 (SD=84 MWh yr^{-1}) MWh yr^{-1}.

7. Conclusion

The potential for shower water heat recovery from bathrooms equipped with instantaneous water heaters in high-rise residential buildings of Hong Kong was investigated. Analysis using a simple single-pass counter-flow heat exchanger that was installed horizontally beneath the shower drain demonstrated a significant energy savings potential. Experiments were conducted to quantify the deficiency of heat exchanger effectiveness in drainage pipe applications. To justify the potential, shower usage patterns including shower operating time and water flow rate sampled from an interview survey as well as water temperatures at the shower heads, shower drains and cold water supply mains measured in sample shower operations were drawn upon. The results indicated that annual energy savings of 4%-15% from shower water heat could be achieved through a 1.5 m long single-pass counter-flow heat exchanger for a drainage pipe of diameter 50 mm. It was noted that assumptions made in the system arrangements, simulations and experimental errors would pose uncertainties to the estimates. Waste heat recovery from shower drains in high-rise residential buildings in hot and humid climates is challenging. Apart from space limitations for the installations, good designs of heat exchanger with justified payback period are essential.

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Glossary

A_o	Heat transfer area (m^2)
$\dot{C}$	Heat capacitance rate (kW °C^{-1})
C_r	Capacitance ratio
c_p	Specific heat capacity (kJ kg^{-1} °C^{-1})
D	Drainage pipe diameter (m)
E	Annual energy consumption (kWh yr^{-1})
i, j	Counts for cases i=1,2,3…; j=1,2,3…n
L	Drainage pipe length (m)
m	Mass flow rate (kg s^{-1})
N_s	Daily shower operations per occupant head count ($head^{-1}$ day^{-1}, denoted as hd^{-1} d^{-1})
NTU	Number of transfer units in heat exchanger
p	p-value of a specified statistic test
$\dot{Q}_1, \dot{Q}_0$	Power consumptions for water heater with and without heat exchanger installation (kW)
R	Sample correlation coefficient
S	Energy saving (%)
t	Time (s)
T	Temperature (ºC)
U_o	Overall heat transfer coefficient (kW m^{-2} ºC^{-1})
Δ	Saving of
ε	Heat exchanger effectiveness
τ	Annual shower operating time (s yr^{-1})
ζ_i	Dummy variable
x	A random number between 0 and 1
<>	Average
<<>>	Standard deviation SD

Subscripts

0, 1, 2, 3	of conditions 0, 1, 2, 3
a	of ambient condition
c	of cold water
h	of hot water
max	of maximum
min	of minimum

Superscripts

~	of a distribution function
−	of average

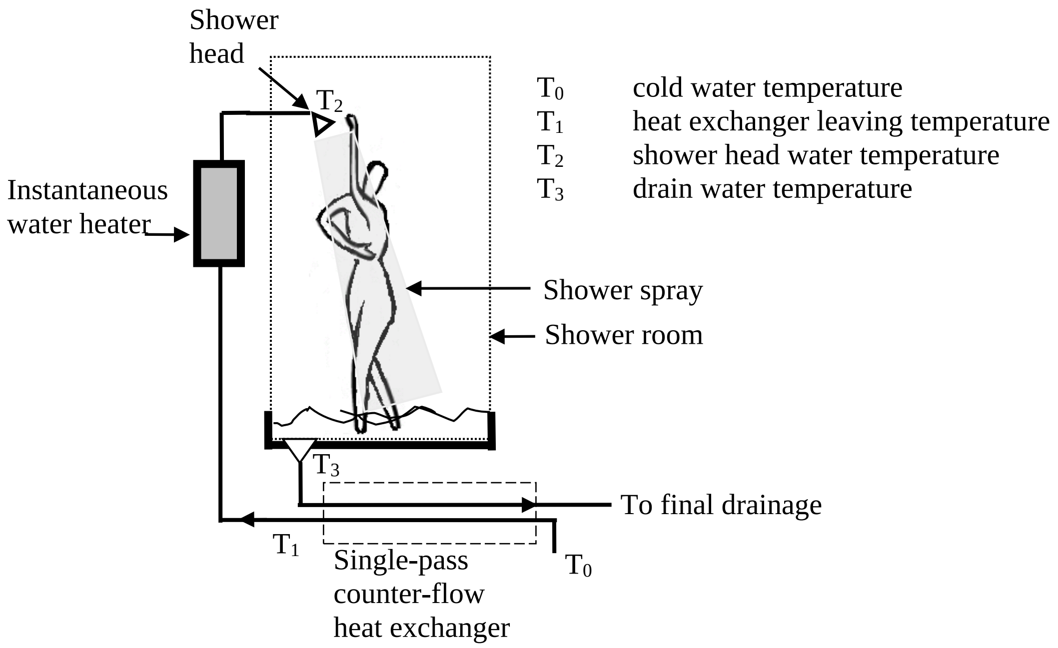


Fig. 1. A typical residential shower installation with a single-pass counter-flow heat exchanger

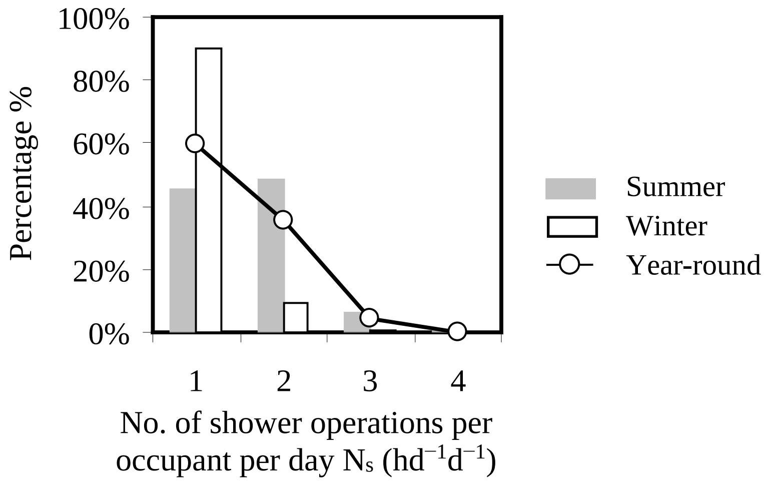


Fig. 2. Daily shower operations per occupant in residential buildings of Hong Kong

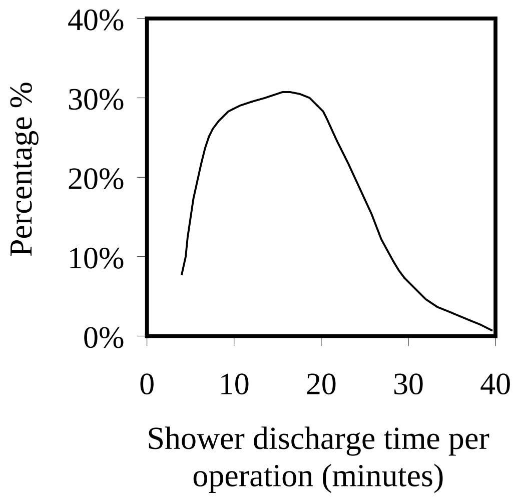


Fig. 3. Shower discharge time of each operation

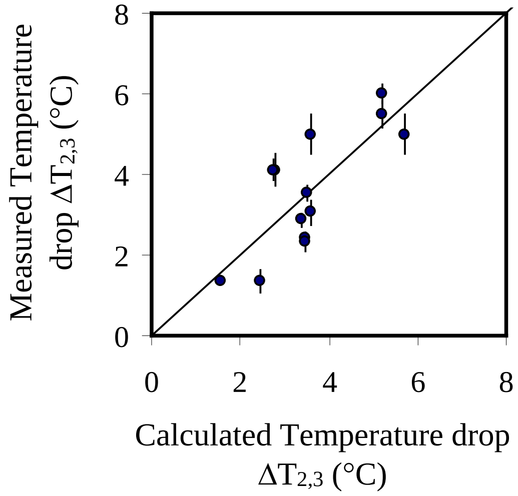


Fig. 4. Measured and calculated Temperature drops from shower head to shower drain

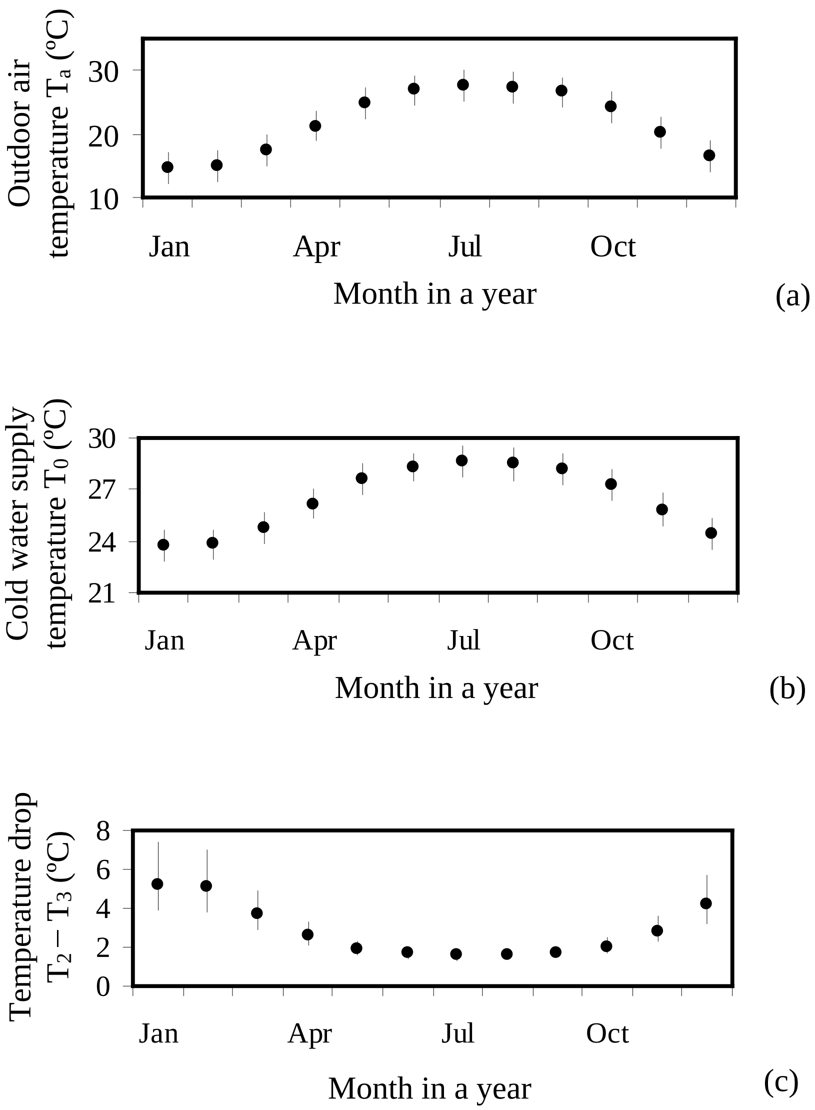
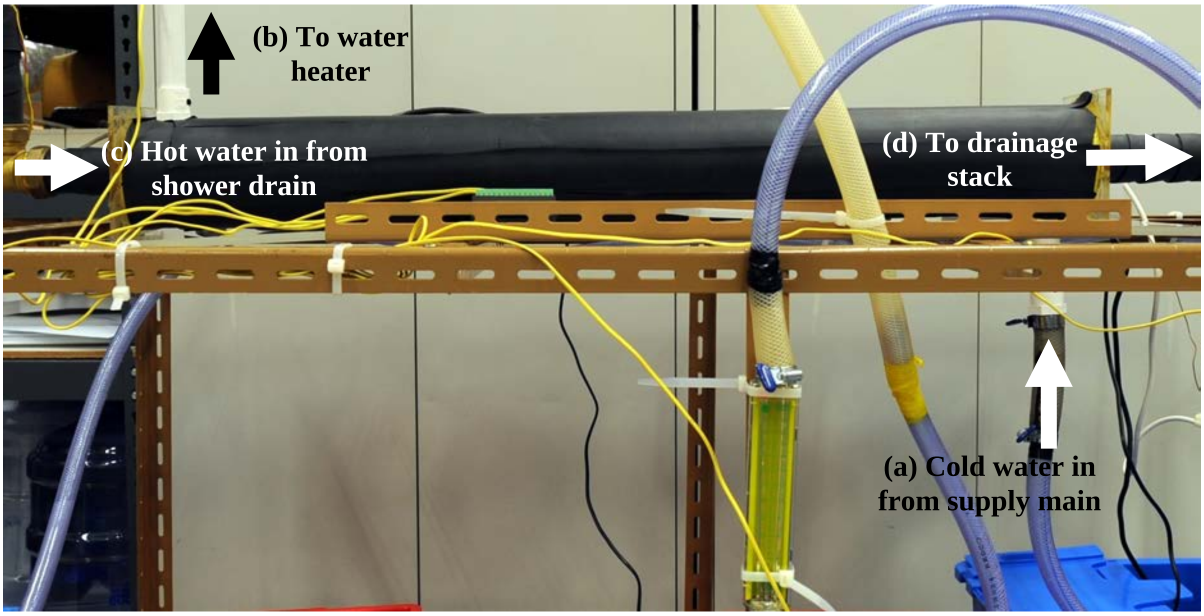
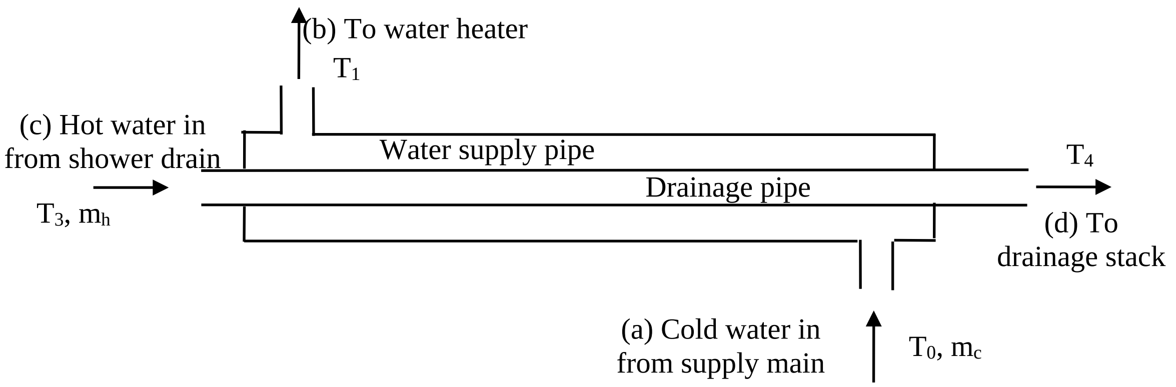


Fig. 5. Monthly profiles of (a) outdoor air temperature; (b) cold water supply temperature; (c) temperature drop of hot water from the shower head (40.9±1.0ºC) to the shower drain



(a) Experimental Setup



(b) Schematic cross-section of the heat exchanger

→ water flow direction

Fig. 6. Experimental setup of a single-pass counter-flow heat exchanger with a partially filled slope hot water drainage pipe

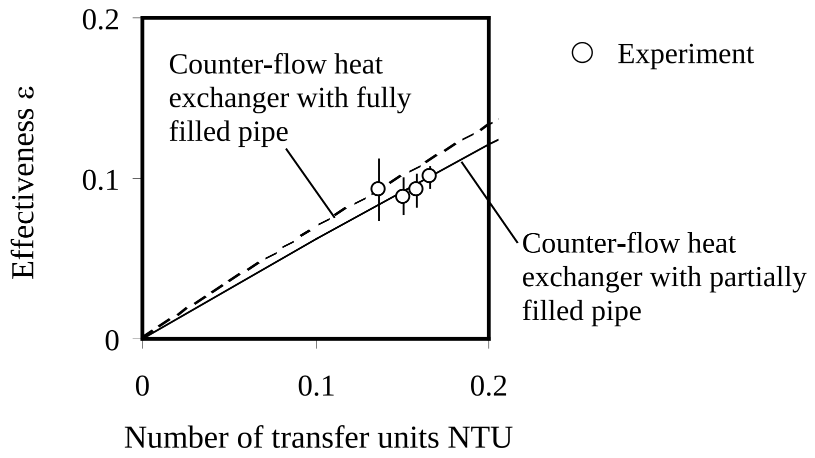


Fig. 7. Counter-flow heat exchanger effectiveness as a function of NTU

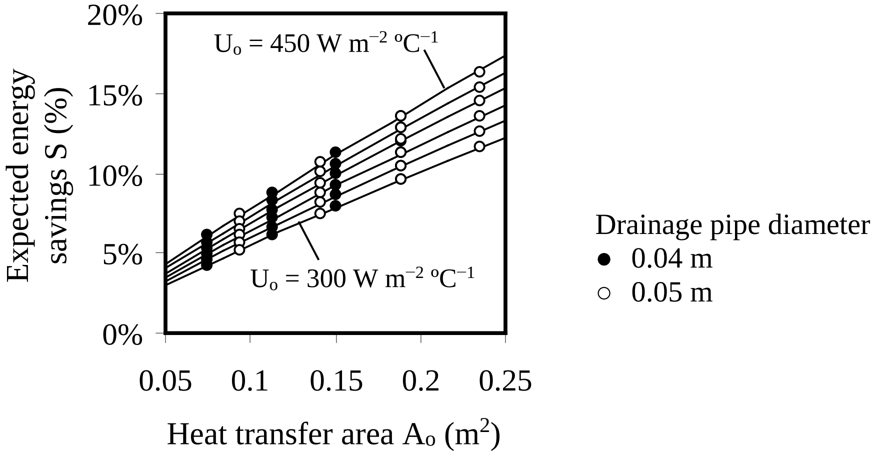


Fig. 8. Expected energy savings from shower water heat