# IMPACT EVALUATION OF LOW FLOW SHOWERHEADS FOR BATHING OF HONG KONG

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# Impact Evaluation of Low Flow Showerheads for Bathing of Hong Kong

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# CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

______________________________ (Signed)

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# Abstract

Water is a global issue identified by United Nations. Residential water consumption accounts for a large portion of total water consumption in commercialized regions or countries, therefore it shows a great water saving potential of residential water use. The use of low flow showerheads is a widely recognized way for residential water conservation nowadays. In order to promote and help consumers choose low flow showerheads, a voluntary Water Efficiency Labelling Scheme (WELS) on showers for bathing has been implemented by Hong Kong government since 2009. Similar schemes were also implemented in Australia, European Union, USA and Singapore.

In this thesis, a comprehensive impact evaluation of low flow showerheads for bathing is performed, and different methods are applied to achieve the objectives, including questionnaire survey, field measurement, Monte Carlo simulation, experimental study and computational fluid dynamics (CFD) simulation. The impact of low flow showerheads for bathing was evaluated from three aspects, namely shower water consumption, and associated energy use and corresponding $CO_2$ emissions; design flow rate of water supply system inside buildings; and aerosol generation rate of showerhead.

The impacts of low flow showerheads for bathing in relation to shower water consumption, associated energy use and corresponding carbon dioxide ($CO_2$) emissions were evaluated first in this thesis. A Monte Carlo model was proposed to evaluate the impact, and the input parameter values of the proposed model were determined from a 5-month measurement survey of the showering practices of 37 Hong Kong residents with a

range of showerheads (with resistance factors $k$=0.54-4.05 kPa min$^2$ L$^{-2}$). The simulation results indicated that, for the limiting case, the installation of low flow showerheads with $k$≥4.02 (≤ 9 L min$^{-1}$) can reduce shower water consumption by 37%, energy use by 25% and $CO_2$ emissions by 26%. This can be a reference for the evaluation of low flow showerheads for bathing on shower water consumption, energy use and $CO_2$ emissions in realistic situation.

As low flow showerheads for bathing brings great reduction of shower water consumption in buildings, a review of water supply system design, i.e. design flow rate, was performed. A mathematical model describing the water demand-and-recovery process inside buildings was given for determination of the inflow rate of up-feed-pipe in an example roof tank water supply system, with installation number of 600 for each type of appliances. The inflow rates were determined by integrating the time series of water demands at the tank with respect to various integrating time periods. Reduced inflow rates (reduction of 15%) of up-feed-pipe was shown when with installation of low flow showerhead in the example water supply system. However, energy efficiency evaluation showed that the reduced inflow rate with unaltered pipe size only increased the system energy efficiency by 1.5%. From the engineering judgement, this implies that it is unnecessary to redesign the inflow rate of water supply system when with low flow showerheads for bathing. For the situation with installation of all types of water efficient appliances, the redesign of inflow rate should be justified further.

Low flow showerheads usually equipped with designs enhancing air mixing in water stream, changing discharging velocity and water spray patterns, it brings new safety concerns related to transmission of Legionnaires' disease (LD) in aerosols which were generated by discharging showerheads. Aerosol generation rate of four sample showerheads, including two conventional showerheads and two low flow ones, were measured in a mechanically ventilated test chamber, assisted by computational fluid dynamics (CFD) simulations. The results showed that the aerosol mass generation rates of four sample showerheads operating at pressure up to 1.5 bar were from $1.42\times10^{-5}$ g $s^{-1}$ to $5.52\times10^{-5}$ g $s^{-1}$, correspondingly aerosol particle generation rates ranged from $0.35\times10^{6}$ particles $s^{-1}$ to $1.35\times10^{6}$ particles $s^{-1}$. Lower aerosol generation rates of low flow showerheads were found when low flow showerhead operating at the same pressure as that of conventional showerheads. The correlations of aerosol generation rate and showerhead attributes were analyzed, and finally a mathematical expression of aerosol generation rate with water supply pressure, spray jet momentum and nozzle area ratio was proposed. This expression can be the referenced guidance for future showerhead design to limit the aerosol generation rate.

The outcomes of this study provide a useful source of reference for water demand management, water supply system design and low flow showerhead design.

## Publications arising from the thesis

Wong, L.T., Mui, K.W., Zhou, Y., 2017. Carbon dioxide reduction targets of hot water showers for people in Hong Kong. Water 9(8), 576.

Wong, L.T., Mui, K.W., Zhou, Y., 2017. Energy efficiency evaluation for the water supply systems in tall buildings. Building Services Engineering Research and Technology 38(4), 400-407.

Wong, L.T., Mui, K.W., Zhou, Y., 2016. Impact evaluation of low flow showerheads for Hong Kong residents. Water 8(7), 305.

Wong, L.T., Mui, K.W., Lau, C.P., Zhou, Y., 2014. Pump efficiency of water supply systems in buildings of Hong Kong. Energy Procedia 61, 335-338.

Zhou, Y., Mui, K.W., Wong, L.T., Tsui, P.H., Chan, W.K. Aerosol generation rates for showerheads. (submitted)

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# List of abbreviations

| | |
|---|---|
| CFD | Computational fluid dynamics |
| CFU | Colony-forming unit |
| $CO_2$ | Carbon dioxide |
| DPM | Discrete phase model |
| EPA | Environmental Protection Agency |
| HKEMSD | Hong Kong Electrical and Mechanical Services Department |
| HKWSD | Hong Kong Water Supplies Department |
| LD | Legionnaires’ disease |
| MMD | Mass median diameter |
| MRF | Multiple Reference Frame |
| MSWC | Murakawa’s simulation for water consumption |
| RAM | Random-across memory |
| RNG | Renormalization Group |
| rpm | Revolutions per minute |
| SD | Standard deviation |
| WC | Water closet |
| WELS | Water Efficiency Labelling Scheme |

# List of symbols

| | |
|---|---|
| $A$ | area |
| $a$ | acceleration |
| $A_f$ | an apartment floor area |
| $C_0$, $C_1$ | proportional constant |
| $C_D$ | coefficient |
| $c_k$ | constant |
| $c_p$ | specific heat capacity of water |
| $C_{pr}$ | aerosol concentration |
| $d$ | diameter |
| $D_s$ | showerhead diameter |
| $E_{out}$ | potential energy required at the demand locations |
| $E_p$ | energy consumption |
| $E_{pump}$ | pumping energy |
| $F$ | force |
| $g$ | gravitational acceleration |
| $h$ | height |
| $H_f$ | friction head loss |
| $H_o$ | desired minimum water pressure head |
| $k$ | showerhead resistance factor |
| $l$ | distance |
| $L_e$ | pipe length |

| | |
|---|---|
| $m$ | mass |
| $m_p$ | per capita annual $CO_2$ emission from hot showers |
| $M_s$ | spray jet momentum |
| $n$ | number |
| $\mathrm{n_a}$ | per-person hourly demand of an appliance |
| $N_a$ | hourly demand of an appliance |
| $N_i$ | number of showers per resident per day |
| $N_p$ | number of persons at a time |
| $O_a$ | occupant-area ratio |
| $P$ | pressure |
| $p$ | probability of a specified statistical test of significance |
| $P_L$ | pressure drop along the water supply pipe |
| $P_s$ | design static pressure at the showerhead |
| $P_t$ | pump power |
| $ps$ | person |
| $q_o$ | inflow rate of up-feed pipe |
| $Q_s$ | water supply flow rate |
| $Q_v$ | ventilation rate |
| $q_w$ | water demand flow rate |
| $Re$ | relative Reynolds number |
| $T$ | temperature |
| $t_s$ | showerhead operating time |
| $T_t$ | integration time scale |

| | |
|---|---|
| $t_{w1,l}$, $t_{w2,l}$ | appliance demand start time and appliance demand end time |
| $u$ | flow velocity |
| $u_s$ | mass flux density |
| $v$ | showerhead flow rate |
| $V_\infty$ | total volumetric water consumption |
| $v^*$ | user preferred showerhead flow rate |
| $v_i$ | volumetric water demand at height $h_i$ |
| $V_o$ | roof tank storage volume |
| $v_o$ | feed pipe water velocity |
| $V_p$ | hot shower water consumption |
| $v_p$ | maximum showerhead flow rate |
| $V_{pr}$ | an aerosol volume |
| $v_s$ | spray jet velocity |
| $\alpha$ | water-$CO_2$ emission factor |
| $\alpha_1$, $\alpha_2$, $\alpha_3$ … | constants |
| $\alpha_t$ | energy efficiency of water supply system |
| $\beta$ | energy-$CO_2$ emission factor |
| $\beta_1$, $\beta_2$, $\beta_3$ … | constants |
| $\gamma$ | occupant load variation factor |
| $\delta_{pr}$ | aerosol volume fraction |
| $\zeta_i$ | parameter |
| $\eta$ | efficiency |
| $\vartheta$ | random number |

| | |
|---|---|
| $\theta_s$ | spray spread angle |
| $\lambda$ | d'Arcy friction coefficient |
| $\lambda_l$ | step length factor |
| $\mu$ | viscosity |
| $\xi$ | loss coefficient |
| $\rho_d$, $\rho_t$ | densities of water and saltwater |
| $\tau$ | time period |
| $\varphi$ | probable satisfaction of consumers |
| $\Phi$ | influence parameter |
| $\phi$ | fraction as defined in an equation |
| $\phi_u$ | water spray uniformity |
| $\chi_s$ | percentage of water volume |
| $\psi$ | energy consumption intensity of water |
| $\omega$ | rotational velocity |
| $\Delta t^*$ | characteristic time |

**Subscripts**

| | |
|---|---|
| *a* | of air |
| *A* | of area |
| *ad* | of additional |
| *a-pr* | of from air phase to aerosol phase |
| *c* | of chamber air |
| *cold* | of cold water |

| | |
|---|---|
| *dr* | of drift |
| *e* | of electric motor |
| *end* | of end |
| *f* | of faceplate |
| *g* | of generation |
| *hot* | of hot water |
| *i* | of inflow |
| *l* | of distance |
| *m* | of mass |
| *ma* | of mass-averaged |
| *max* | of maximum |
| *mt* | of mechanical transmission |
| *o* | of outflow |
| *ov* | of overall |
| *p* | of pump |
| *pr* | of particle/aerosol phase |
| *pr-a* | of from aerosol phase to air phase |
| *process* | of water supply process |
| *r* | of reading |
| *relat* | of relative |
| *s* | of shower |
| *t* | of total |

| | |
|---|---|
| $w$ | of wall |
| 0 | of left on electronic scale |
| 1,2,3 | of shower nozzle diameter 1 mm, 2 mm, 3 mm |

**Superscripts**

| | |
|---|---|
| . | of change rate with respect to time |
| ′ | of gradient |
| - | of average |

# Chapter 1

# Introduction

## 1.1 Background

Water is a global issue nowadays as identified by United Nations (United Nations 2017). Due to population and economy growths as well as climate change, many countries and regions are facing water scarcity. Water scarcity affects more than 40% of the global population, and is projected to rise (United Nations 2017). Water conservation as a way to deal with water scarcity arises considerable concern in current society. As domestic water consumption usually accounts for a large portion of total water consumption in commercialized nations or regions, such as 45% in Singapore (Singapore's National Water Agency 2017), 66% in Gold Coast, Australia (Willis et al. 2013), and above 50% in Hong Kong (Hong Kong Water Supplies Department (HKWSD) 2015), it shows a great water saving potential of domestic water use.

The Paris Agreement adopted under the United Nations Framework Convention on Climate Change (UNFCCC) established the global frameworks for reducing carbon dioxide ($CO_2$) emissions to response to the threat of climate change (Sutter and Berlinger 2015). As energy is consumed at each stage of water cycle, like water extraction and treatment, water distribution, end use, wastewater treatment and disposal (Plappally and Lienhard 2012, United States Environmental Protection Agency (EPA) 2017a), water systems have been identified as a strategic area of energy-related $CO_2$ emission reduction (Zhou et al. 2013). Some reference data about energy consumption in water system and corresponding $CO_2$ emissions are listed below, clearly, the reduction potential of energy use and $CO_2$ emissions related to water systems is great.

> In U.S., the water-related energy use accounted for 13% of the nation's electricity consumption (Sattenspiel and Wilson 2009). Example showed that 19% of electricity consumption in California came from the water cycle, in which 72% of the electricity consumption in the water cycle occurred at the end use (Plappally and Lienhard 2012). In Hong Kong, about 18% of residential energy consumption in 2013 was used to provide hot water for showers and baths (Hong Kong Electrical and Mechanical Services Department (HKEMSD) 2017).

> In U.S., the $CO_2$ embodied in nation's water represented 5% (290 million metric tons of $CO_2$ emission a year) of all U.S. carbon emissions (Sattenspiel and Wilson 2009). In UK, only end-use of heating hot water had accounted for 5.5% (35 million metric tons of $CO_2$ emission a year) of total $CO_2$ emissions (Environmental Agency 2008). In Japan, residential water supply systems accounted for 5% of total $CO_2$ emissions and about 60% of these emissions were from hot water bathing (Okamoto et al. 2015). In Austria, a study showed that the $CO_2$ emissions caused by energy consumption from hot showers ranged between 160 and 245 kg-$CO_2$ (person)ps$^{-1}$ yr$^{-1}$ (Beal et al. 2010a).

The $CO_2$ emissions related to energy use in water systems can be reduced by: (1) better design of water delivery, (2) water efficiency improvement. First, energy can be saved by better system designs for water delivery, such as by choosing suitable pumps with efficient operation and maintenance schedules (Kaya et al. 2008, Wong et al. 2016). Energy efficiency improvements by roof tank water supply systems for buildings was studied (Cheung et al. 2013), and it showed that energy consumptions of many existing high-rise water supply systems could be reduced up to 50% via pressure rezoning by water storage tank relocations. Second, water efficient appliance offers a lower water demands which cause reduction on energy use for water pumping, treatment and end-use heating (Cheng 2002, Shimizu et al. 2012b, Zhou et al. 2013). Low flow showerheads are found to be an effective means of saving water which the shower bathing is predominated by the usage time (Okamoto et al. 2015). It was reported that the overall carbon emission in Japan could be reduced by 1% due to the adoption of water saving equipment (Otani et al. 2015). The reduction is more significant in developing area because water supply is one of the major energy consumers. In Vietnam, the potential reduction was estimated to be 8.8% of total $CO_2$ emissions by widespread adoption of water saving equipment.

In order to promote the water efficient appliances, water efficiency labelling schemes on water consuming appliances have been proposed and implemented in many countries or regions, like the Water Efficiency Labelling and Standards (WELS) scheme in Australia (Australian Government 2017a), Water Efficiency Labelling Scheme (WELS) in Singapore (Public Utilities Board 2013), WaterSense in USA (United States Environmental Protection Agency 2017b), European Water Label in European Union (The Water Label Company Limited 2017), and the voluntary Water Efficiency Labelling

Scheme (WELS) in Hong Kong (hereafter, WELS in following chapters refers to the voluntary Water Efficiency Labelling Scheme in Hong Kong) (Hong Kong Water Supplies Department 2017). The water efficiency labelling schemes provide information on appliance water consumption for manufacturers and consumers. It helps consumers select water efficient plumbing fixtures and water consuming appliances. In Hong Kong, the WELS is a voluntary scheme and has been implemented in phases for different groups of plumbing fixtures and water consuming appliances, currently covering showerheads, water taps, washing machines, urinal equipment and flow controllers. Any plumbing fixtures and water consuming appliances that fulfil the WELS performance requirements can be registered under the scheme. The registered plumbing fixtures and water consuming appliances are grouped based on the level of water consumption and water efficiency. Take showerhead as an example, according to their nominal flow rates, all registered showerheads are classified into four water efficiency grades, namely Grade 1: $\leq$0.15 $Ls^{-1}$, Grade 2: 0.15-0.2 $Ls^{-1}$, Grade 3: 0.2-0.27 $Ls^{-1}$ and Grade 4: $\geq$0.27 $Ls^{-1}$.

However, a comprehensive evaluation related to the impact of water efficient appliances is still limited at the moment. Therefore, this thesis will try to fill this gap.

## 1.2 Local issues in Hong Kong

In order to save fresh water resources, salt water (sea water) has been used for toilet flushing since the 1950s in Hong Kong, and the current salt water supply coverage is about 80% of the total population (Hong Kong Water Supplies Department 2015). Except water closet (WC), other appliances in buildings are supplied by fresh water systems. In Hong Kong, over 40% of the domestic fresh water consumption is used for showers for bathing (Hong Kong Water Supplies Department 2011b), and energy use for shower bathing water heating in residential buildings in 2015 was about 18% of total energy consumption (25% was for space conditioning) (Hong Kong Electrical and Mechanical Services Department 2017). As showers represent a significant share of household water use, showerhead was selected and prioritized for inclusion in the phased WELS in Hong Kong (in September 2009). Therefore, this thesis will specifically evaluate the impact of low flow showerheads for bathing. The direct impact, i.e. on the shower water consumption, of low flow showerheads for bathing will be evaluated first.

Hong Kong is a densely populated city, with approximately 7.3 million population living in less than 25% developed land out of total 1105 $km^2$ area (Hong Kong Government 2017). High-rise housing is a trend in Hong Kong, which leads to the correspondingly large and complex plumbing systems. Gravity storage tanks on rooftops distributing water through down-feed pipes are common water supply systems in Hong Kong high-rise buildings. As large and complex plumbing systems feed large amount of demand points, the adoption of low flow showerheads in high-rise buildings may contribute to great reduction of shower water consumption for the whole water system, and further influence the water supply system design. The indirect impact, i.e. on the water supply system design (i.e. design flow rate), of low flow showerheads for bathing will also be evaluated.

Besides issues of shower water consumption and water supply system design that related to low flow showerheads for bathing, another concerned issue is the aerosol concentration in the bathroom. It has been recognized that aerosols are generated with water consuming appliance discharging, which provide a transmission medium of Leionnaires' disease, a severe pneumonic illness caused by bacterium *Legionella pneumophila*. *Legionella pneumophila* can be transmitted to humans from potable water systems via inhalation of aerosols generated by the discharging appliances (Bollin et al. 1985, Fields et al. 2002). In Hong Kong, Legionellosis has been a reportable disease since 1994 (Berger 2017). The number of reported cases of LD has been rising in Hong Kong in recent years, from 17 cases in 2011, to 28 each in 2012 and 2013, 41 in 2014 and 66 in 2015 (Center for Health Protection 2016). Among the recently reported LD cases, 4 (3–17.2 CFU $ml^{-1}$) out of 10 (3–72.4 CFU $ml^{-1}$) legionella-positive water samples were from bathroom showers (Hong Kong Government 2016). Infectious aerosol exposures are associated with aerosol concentration, aerosol size distribution, breathing rate, exposure time and immunity (Carson 1996, Kowalski 2006), in which, for definite ventilation style, the aerosol concentration in the space (e.g. bathroom) is related to the aerosol generation rate of showerheads. Among the several factors that influence the LD infection, aerosol generation rate of low flow showerhead will be evaluated specifically in this thesis. The discussions about why only focus on the study of aerosol generation rate will be further described in Chapter 2.

## 1.3 Research objectives

The impact of low flow showerheads for bathing is evaluated from three aspects, and corresponding three objectives are defined:

1. To quantify the reduction of shower water consumption in households, as well as associated energy use and corresponding $CO_2$ emissions with the use of low flow showerheads for bathing.
2. To examine the design flow rate for water supply systems inside buildings replaced with low flow showerheads installed.
3. To determine the aerosol generation rate of low flow showerheads, and identify its contributing factors.

## 1.4 Research scope

Generally, this thesis focuses on the impact evaluation of low flow showerheads for bathing of Hong Kong, so that data collection and analysis in this thesis, such as household water consumption, water supply system type, and appliance samples, are all based on the Hong Kong situations.

Detailed research scope for the three defined objectives is described below, and steps for achieving these objectives are given.

1. For the first objective, the limiting case that showing the theoretically maximum benefits (i.e. reduction of shower water consumption, energy use and $CO_2$ emissions) of low flow showerheads for bathing is evaluated. Mathematical models for quantifying the shower water consumption, as well as associated energy use and corresponding energy-related $CO_2$ emissions are proposed. The theoretically maximum reduction of shower water consumption, energy use and $CO_2$ emissions of low flow showerheads bathing is given by Monte Carlo simulations using the proposed mathematical models.
2. For the second objective, typical roof tank water supply system in high-rise buildings in Hong Kong is selected for the redesign justification as a response to the variation of household water consumption after with the low flow showerheads for bathing. Redesign justification of municipal water supply system is not included in this study. The water supply system feeds different types of appliances, including showerheads, wash basins, kitchen sinks and washing machines. Mathematical models for estimating design flow rate of water supply system are

developed. Two cases of design flow rate are simulated: Case A is that all types of appliances are conventional ones; Case B is that showerheads are low flow ones, while other types of appliances are conventional ones. The simulated design flow rates for the two cases are compared and evaluated from energy efficiency aspect. Energy efficiency model for water supply system is proposed to evaluate the simulated design flow rates.

3. The input parameter values of the proposed mathematical models in the first and second objectives are from open literatures and one new showering questionnaire survey and field measurement. Local residents are recruited for the showering questionnaire survey, and parameters of sample showerheads that bought from local market are measured.

4. For the third objective, a mathematical expression of aerosol mass balance in ventilated space with aerosol generation source inside is developed, which includes terms of aerosol mass generation rate, aerosol mass exhaust rate and aerosol deposition fraction. Aerosol generation rate of sample showerheads (that bought from local market, including conventional ones and low flow ones) is experimentally studied in a ventilated test chamber. Aerosol mass exhaust rate is acquired from the experimental study. Computational fluid dynamics (CFD) simulations of aerosol generation in the chamber is carried out, and aerosol deposition fraction on the chamber walls is obtained from the simulations. Based on the results of the experimental study and CFD simulations, aerosol generation rates of sample showerheads are determined by the developed aerosol mass balance equation. Aerosol generation rates of conventional showerheads and low

flow ones are compared. Statistical analysis of aerosol generation rate and influence parameters is performed, and expression of aerosol generation rate by showerhead attributes is developed.

## 1.5 Outline of the thesis

Background information about carrying out this research is provided in Chapter 1, and the necessity for the study in Hong Kong is shown. Research objectives are identified and research scope is defined in Chapter 1.

Chapter 2 reviews the historical development of water efficiency labelling schemes as a water conservation policy in households first. Then the three aspects that related to the low flow showerheads for bathing are reviewed, namely water consumption and associated energy use and corresponding $CO_2$ emissions; water supply system design; and aerosol generation rate of water consuming appliances. Corresponding research problems for each aspect are determined. Existing evaluation methods for each aspect are given and limitations are discussed.

Chapter 3 describes the different methods adopted in this thesis in detail. A 5-month showering questionnaire survey and field measurement in sample residential washrooms are described first. Then, Monte Carlo models for per capita annual shower water consumption as well as associated energy use and corresponding $CO_2$ emissions are proposed. Besides, another Monte Carlo models for simulating design flow rate of water supply system inside buildings are also developed. Experimental study and computational fluid dynamics (CFD) simulations of aerosol generation of showerhead in test chamber are introduced, and mathematical expressions for determining the aerosol generation rate of showerhead are developed. Regression analysis is introduced for the analysis of the collected data.

The impact of low flow showerheads for bathing on shower water consumption as well as associated energy use and corresponding $CO_2$ emissions are reported in Chapter 4. The surveyed and measured results about showering in local residential washrooms are given and discussed first. Then, correlations among shower water consumption, showerhead properties and consumer satisfaction are analyzed. After that, Monte Carlo simulation results of shower water consumption as well as associated energy use and corresponding $CO_2$ emissions are given and discussed.

The influence of the shower water consumption reduction as the low flow showerheads for bathing on the water supply system design is reported in Chapter 5. Surveyed appliance demands are described first. Simulated water demand time series and design flow rate of water supply system are then given. Following, energy efficiency evaluation about the simulated design flow rate is presented.

The aerosol generation rates of conventional and low flow showerheads are reported in Chapter 6. Four sample showerheads and its physical properties and spray attributes are introduced. Experimental and CFD simulation results about the aerosol mass generation rates of the four sample showerheads are presented. Correlations between aerosol mass generation rate and showerhead attributes are analyzed, and quantified expression is proposed. Aerosol generation rates of low flow showerheads are discussed and measures for limiting showerhead aerosol generation rates are recommended.

Chapter 7 summarizes the key findings, implications and future research suggestions. Research limitations are also given.

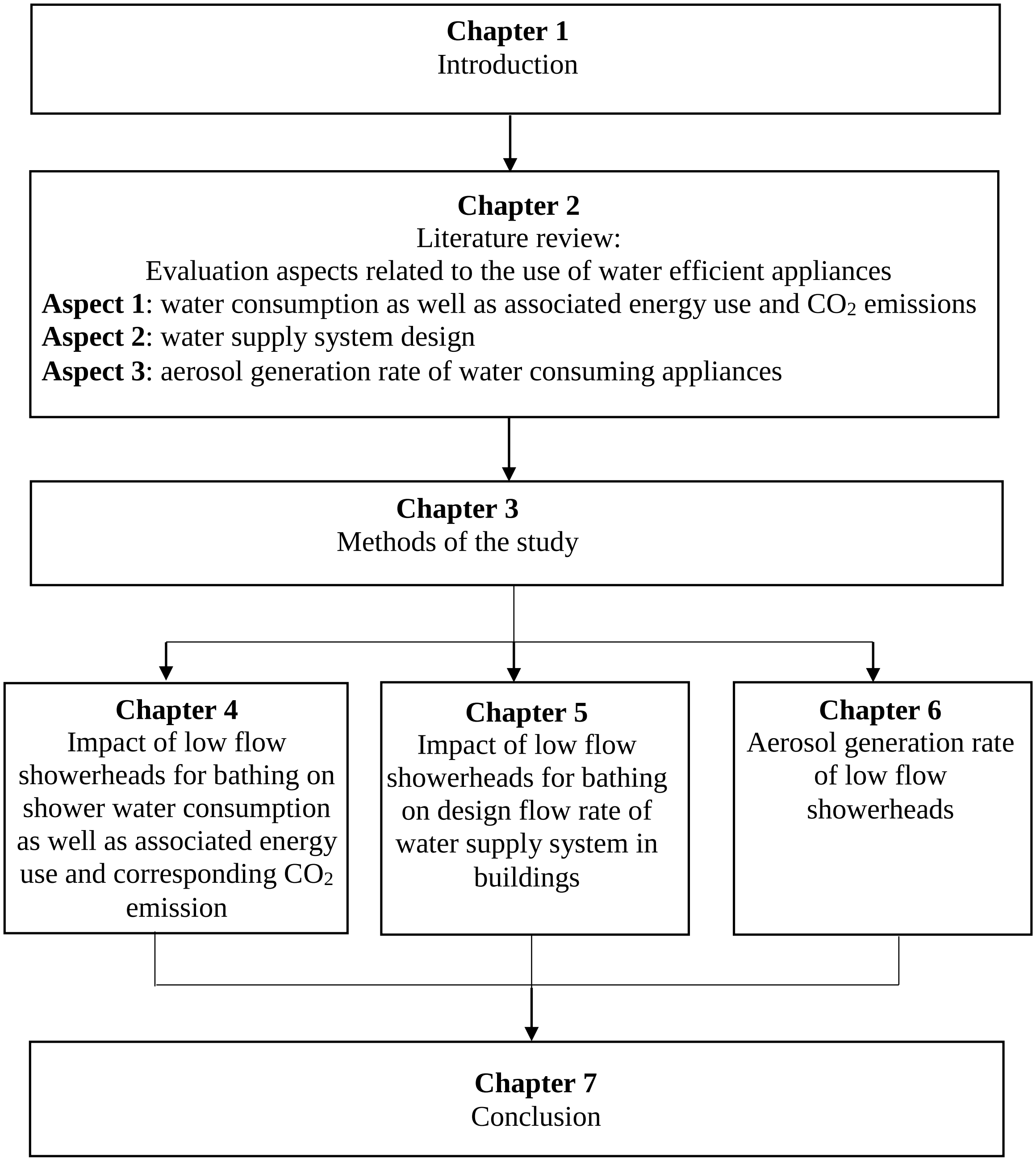



**Figure 1.1 Logic diagram of the thesis**

# Chapter 2

# Review on evaluation aspects of low flow showerheads for bathing

The historical development of water efficiency labelling schemes as a water conservation policy will be reviewed first in this section. Then the usual evaluation aspects related to low flow showerheads for bathing will be identified by reviews and corresponding research problems in each evaluation aspect will be determined.

## 2.1 Historical development of water efficiency labelling schemes

Policymakers and water providers increasingly rely on demand-side water management as a means to promote water conservation in the residential sector (Renwick and Archibald 1998, Millock and Nauges 2010). Two types of demand-side management were distinguished from previous literatures, namely price and non-price policies (Krause et al. 2003, Kenney et al. 2008, Price et al. 2014), and were outlined in Figure 2.1.

Price policies have received much attention by economists who consider that higher water price could induce water demand reduction (Renwick and Archibald 1998, Roibas et al. 2007, Grafton and Ward 2008). Previous studies did show that water price affects water demand quantity (Howe and Linaweaver 1967), however, it was also revealed that price elasticity of demand for water is inelastic at current prices, making price to be a relatively ineffective demand-side management policy (Howe and Linaweaver 1967, Bruvold 1990, Arbues et al. 2003, Dalhuisen et al. 2003, Price et al. 2014). It was also argued that lower income households would bear a larger share of the conservation burden by the price policy (Renwick and Archibald 1998).

Partially due to above reasons, water providers/water utilities managers have often preferred to utilize non-price policies (Olmstead et al. 2007). Non-price policies refer to a wide range of interventions, including restrictions on water use such as rationing, public education campaigns, subsidies for low-flow appliances, and low-flow engineering requirements on new plumbing fixtures (Price et al. 2014). One more popular non-price policies are rebate/retrofit programs for the installation of water efficient appliances (e.g. toilets, showerheads and washing machine) (Millock and Nauges 2010, Price et al. 2014). Compared to water price increase and water restrictions, policies to promote the installation of water efficient appliances are more politically acceptable (Millock and Nauges 2010); besides, it was revealed that as the pervasive role of habits in human behavior, it makes policy of public information campaigns yield little effect (ThØgersen and Olander 2002).

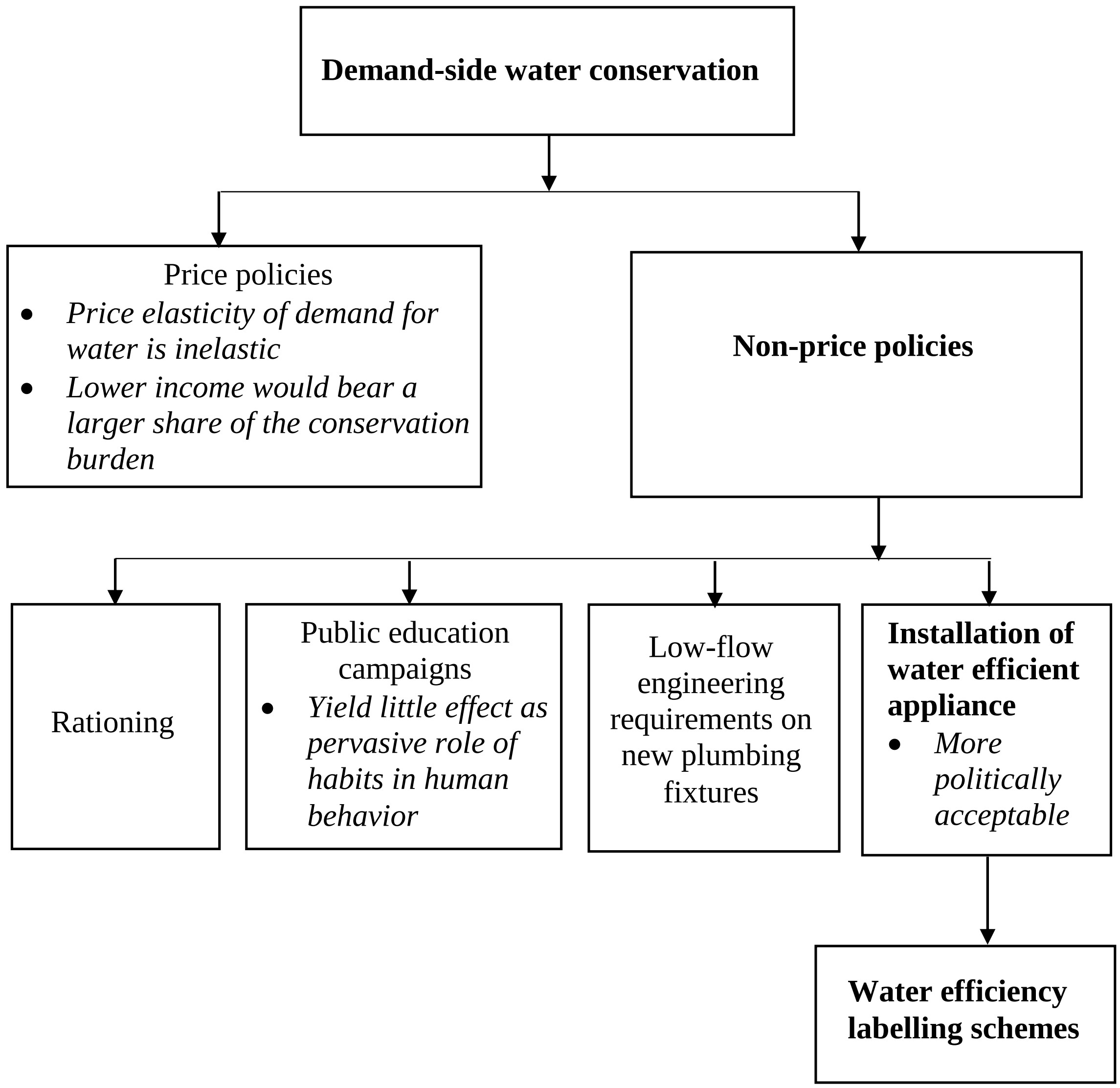



**Figure 2.1 Logic diagram of demand-side water conservation policies**

Correspondingly, water efficiency labelling schemes on water consuming appliances have been proposed and implemented in many countries or regions around the world (e.g. Australia, Singapore, USA, Europe and Hong Kong), as summarized in Table 2.1, in order to promote and help consumers choose water efficient appliances. Australia is an early country that began the scheme in 2005, and from 1 July 2006, the scheme becomes mandatory; all new products (showers, tap equipment, flow controllers, lavatory equipment, urinal equipment, dishwashers, clothes washing machines, the dryer function of combination washer/dryers, where they use water to dry a load) supplied across Australia must be registered and labelled before they can be sold (Australian Government 2017b). The Singapore Water Efficiency Labelling Scheme (WELS) is also mandatory, for water fittings and appliances including shower taps and mixers, basin taps and mixers, sink/bib taps and mixers, dual flush low capacity flushing cisterns, urinal flush valves, waterless urinals, clothes washing machines intended for household use; only showerheads are covered under voluntary WELS (Public Utilities Board 2013).

In Hong Kong, a voluntary Water Efficiency Labelling Scheme (WELS) has been implemented in phases for different groups of plumbing fixtures and appliances, e.g. showerheads (in September 2009), water taps (in September 2010), washing machines (in March 2011), urinal equipment and flow controllers (in March 2012), by the Hong Kong Water Supplies Department (HKWSD) since 2009 (Hong Kong Water Supplies Department 2017). Similar voluntary schemes include WaterSense in USA (United States Environmental Protection Agency 2017b) and European Water Label (The Water Label Company Limited 2017). The WaterSense program label takes the form of an endorsement or mark of approval rather than a ranking (European Commission (DG ENV) 2009). As shown in Table 2.1, the water performance requirement of products varies with countries and regions; taking showerhead performance as an example, the requirements are 6-7 L min$^{-1}$ and 5-9 L min$^{-1}$ under the Water Efficiency Labelling and Standards (WELS) scheme in Australia and Water Efficiency Labelling Scheme (WELS) of

Singapore respectively, however, it is 9-16 L $min^{-1}$ under the WELS of Hong Kong. The requirement difference may be caused by the water resource situations in different countries and regions.

The Hong Kong government has taken a leading role to install water saving appliance in government projects and buildings, in which about 52600 water saving appliances (low flow showers, dual flush cisterns, sensor type urinals and low flow sensor type water taps) (Lee 2013) and 80000 flow controllers (Hong Kong Water Supplies Department 2015) have been installed respectively till 2013 and 2015. Review study in 2015 revealed that almost two-thirds of the homes in the United States were equipped with the original fixtures that were installed when the house was built (GMP Research Inc. 2015). The market penetration of WaterSense toilets, lavatory faucets and showerheads were 7%, 25.4% and 28.7% respectively (GMP Research Inc. 2015). Since the program's inception in 2006, the total number of WaterSense labeled models has increased to 16110 till 2015, and the cumulative water saving was 1.5 trillion gallons of water (United States Environmental Protection Agency 2015). As the penetration of water efficient appliances increases gradually after a period (several years) of the implementation of water efficiency labelling schemes, correspondingly the impact evaluation of the use of the water efficient appliances becomes necessary.

**Table 2.1 Summary of some water efficiency labelling schemes in the world**

| Country or region | Item | Type | Products covered | Water performance requirement | Reference |
|---|---|---|---|---|---|
| Australia | Water Efficiency Labelling and Standards (WELS) scheme | Mandatory | All new products, including showers, tap equipment, flow controllers, lavatory equipment, urinal equipment, dishwashers, clothes washing machines, the dryer function of combination washer/dryers | e.g.<br>Toilets: ≤ 5.5 L $flush^{-1}$;<br>Showerheads: 6 to 7 L $min^{-1}$;<br>Taps: ≤ 2 L $min^{-1}$;<br>Urinals: 1.5 L $flush^{-1}$ | AS/NZS 6400: 2005AS/NZS 6400: 2005 |
| Singapore | Water Efficiency Labelling Scheme (WELS) | Mandatory & Voluntary | Shower taps and mixers, basin taps and mixers, sink/bib taps and mixers, dual flush low capacity flushing cisterns, urinal flush valves, waterless urinals, clothes washing machines intended for household use (mandatory);<br>Showerheads (voluntary) | e.g.<br>Toilets: > 2.5 to 4.5 L $flush^{-1}$;<br>Washing machine: 6 to 12 L $kg^{-1}$;<br>Showerheads: ≤ 5 to 9 L $min^{-1}$;<br>Shower taps and mixers: ≤ 5 to 9 L $min^{-1}$;<br>Basin taps and mixers: ≤ 2 to 6 L $min^{-1}$;<br>Sink taps: 4 to 8 L $min^{-1}$;<br>Urinals: 0.5 to 1.5 L $flush^{-1}$ | Public Utilities Board (2013) |
| USA | WaterSense | Voluntary | Water efficient products (residential toilets, showerheads, bathroom faucets, commercial toilets, urinals, pre-rinse spray valves, irrigation controllers), homes and professional certification programs | Products bearing the WaterSense label are generally 20 percent more water-efficient than similar products in the marketplace | United States Environmental Protection Agency ( 2017b) |

**Table 2.1 Continued**

| Country or region | Item | Type | Products covered | Water performance requirement | Reference |
|---|---|---|---|---|---|
| European Union | European Water Label | Voluntary | Bath, water closet (WC) suit, cistern, basin tap, shower control, shower handset, grey water recycling unit, kitchen tap, urinal controller, electric shower, replacement WC flushing device, supply line flow regulator, independent WC pan | – | The Water Label Company Limited (2017) |
| **Hong Kong** | **Water Efficiency Labelling Scheme (WELS)** | **Voluntary** | **Showerheads**, water taps, washing machines, urinal equipment, flow controllers | e.g.<br>**Showerheads: ≤ 9 L/min to 16 L $\mathbf{min^{-1}}$**;<br>Non-mixing type water taps: ≤ 2 to 6 L $min^{-1}$;<br>Mixing type water taps: ≤ 5 to 9 L $min^{-1}$;<br>Horizontal drum type washing machines: ≤ 9 to 13 L $kg^{-1}$ $cycle^{-1}$;<br>Impeller type or agitator type washing machines: ≤ 16 to 22 L $kg^{-1}$ $cycle^{-1}$;<br>Urinal equipment: ≤1.5 to 4.5 L $cycle^{-1}$;<br>Flow controllers for water taps: ≤ 5 to 9 L $min^{-1}$;<br>Flow controllers for showers for bathing: ≤ 9 to 16 L $min^{-1}$ | HKWSD (2017) |

## 2.2 Evaluation aspect 1: Household water consumption as well as associated energy use and corresponding $CO_2$ emissions

One direct influence of using water efficient appliances is on the water use, and several studies have been done to evaluate the influence (Campbell et al. 2004, Price et al. 2014). Among these studies, collecting and analyzing water consumption data, some are a great amount of data, in households is a usual method for the evaluation. For example, in Compbell et al.'s (2004) work, the water consumption evaluation was based on a dataset that comprised of more than 200000 monthly observations of more than 19000 household accounts over six years. In the study by Price et al. (2014), monthly water use data and rebate receipts of nearly 520000 households between 1994 and 2008 were obtained from water utility authority, and the average daily water use of pre- and post- installation of water efficient appliances was calculated and used for regression analysis. Price et al.'s (2014) study showed that the combination of a single water efficient toilet and showerhead reduced average water demand by 16.25% or 46.69 gallons per day per household, in which water efficient showerhead reduced water demand by 8.71 gallons. In the study by Renwick and Archibald (1998), panel regression techniques were used to investigate the effect of low-flow technology on household water demand in California, and it showed that water efficient toilets and showerheads reduced water consumption by 10% and 8% respectively. In all these studies, the impact of water efficient appliances on water use was evaluated on household level. Besides, the influence of seasonal variation on water use was not included in the evaluation. As the number of residents and installed water efficient appliances varies in different household, the obtained water use reduction by water efficient appliances on household level cannot be an optimal reference benchmark.

Besides, as the water use habits/behaviors of different residents are usually different, the individual diversity of water use cannot be reflected by the household level evaluation. It can be seen that the evaluation of water use on individual level for a specific water efficient appliance is needed. The individual-level evaluation results can be a direct feedback information of the appliance water efficiency and be a reference source for modifying water efficient appliance design as well as modifying the water efficiency labelling schemes.

Specific investigations about water consumption by water efficient showerheads were conducted in some countries or regions. In the survey conducted by Yamazaki et al. (2013) in 7 Vietnam households, reduction of water consumption per shower bathing was found after replacement of water efficient showerhead. Water saving by water efficient showerheads was also reported by Lee et al. (2015) for the investigation of shower water use in 44 Taiwan households. According to the recorded water use by smart water meter and residents' self-reported water diary, the study in Gold Coast, Australia showed that changing low efficiency showerheads to high efficiency showerheads could achieve annual per capita water saving of 11.3 kL (Willis et al. 2013). Willis et al.'s (2013) study also showed that showerhead retrofit is one of the least cost water demand management initiatives available to water businesses and government (Willis et al. 2013). According to all these previous studies, the water conservation potential by installation of water efficient appliances, including water efficient showerheads, has been validated generally.

The indirect influence of using water efficient appliances includes the energy use that related to the water consumption, and further the energy-related $CO_2$ emissions. Energy is consumed at each stage of water cycle, like water treatment, supply, use and disposal (Plappally and Lienhard V 2012). Therefore, water consumption directly influences the energy use, and subsequently the $CO_2$ emissions. The reduction potential of $CO_2$ emissions by water efficient appliances in households is noticed, and the association between water use and $CO_2$ emissions has been studied widely in recent years (Kenway et al. 2008, Hackett and Gray 2009, Shimizu et al. 2012a).

To evaluate the $CO_2$ emissions from water use, the concept of $CO_2$ emission factor for water (kg-$CO_2$ $m^{-3}$) was proposed and calculated by product of energy consumption intensity of water (kWh $m^{-3}$) and $CO_2$ emission factor for energy (e.g. electricity) (kg-$CO_2$ $kWh^{-1}$) in several studies (Hackett and Gray 2009, Cheng et al. 2012, Shimizu et al. 2012a, Toyosada et al. 2012). The logic for the calculation of $CO_2$ emissions from water use is presented in Figure 2.2. For the calculation of energy consumption intensity of water in these studies, different calculation boundaries of energy consumption were defined. Plappally and Lienhard V (2012) studied the energy consumption intensity of water (kWh $m^{-3}$) by life cycle analysis of energy consumption in the water cycle, including stages of water production, municipal water treatment, water distribution, end use, waste water collection, waste water treatment, waste water discharge, recycled water treatment and recycled water distribution in the water cycle was considered, and different sources of energy were converted into equivalent electricity in unit of kWh (Plappally and Lienhard V 2012). In Shimizu et al.'s (2012a) and Toyosada et al.'s (2012) studies, only energy consumption for operation of waterworks (i.e. water intake, water purification, water distribution not including pumping inside buildings) and sewer system (i.e. transfer by pump, water treatment, sludge disposal) was considered; energy consumption for end use and water recycle was not included. Comparatively, Cheng et al. (2012) added the pumping energy consumption inside buildings for the calculation of energy consumption intensity of water. It can be seen that for the calculation of energy consumption intensity of water, definition of the energy calculation boundary for a specific study is necessary.

As the differences of specific technologies applied at each stage of the water cycle, location situation, human behavior and local culture, the energy consumption intensity of water was found significantly different in different countries or regions, e.g. 50.69-68.2 kWh $m^{-3}$ in Australia, 73.24-87.06 kWh $m^{-3}$ in California, 47.16-47.81 kWh $m^{-3}$ in Ontario, Canada (Plappally and Lienhard V 2012). Comparatively, the calculated energy consumption intensities of water were 1.012 kWh $m^{-3}$ in Japan (Shimizu et al. 2012a), 0.78 kWh $m^{-3}$ in Taiwan (Cheng et al. 2012) and 1.37 kWh $m^{-3}$ in China (Toyosada et al. 2012). These values of energy consumption intensity of water are greatly different from that reported by Plappally and Lienhard V (2012), which was due to the difference of calculation boundaries of energy consumption, e.g. energy consumption for end use was included in Plappally and Lienhard V's (2012) study, but not in others (Cheng et al. 2012, Shimizu et al. 2012a, Toyosada et al. 2012). This validates the necessity of defining energy calculation boundary for the calculation of energy consumption intensity of water. The energy intensity of end use was found very high relative to other stages of the water cycle, in which hot water usage was the most energy intensive in the residential sector (Plappally and Lienhard V 2012). According to the energy end-use report by Hong Kong Electrical and Mechanical Services Department in 2015, the energy consumed by each capita within the residential sector was 8.3 GJ in 2013, in which 19% of the energy consumption was used for heating hot water (excluding hot water used in cooking) (Hong Kong Electrical and Mechanical Services Department 2017).

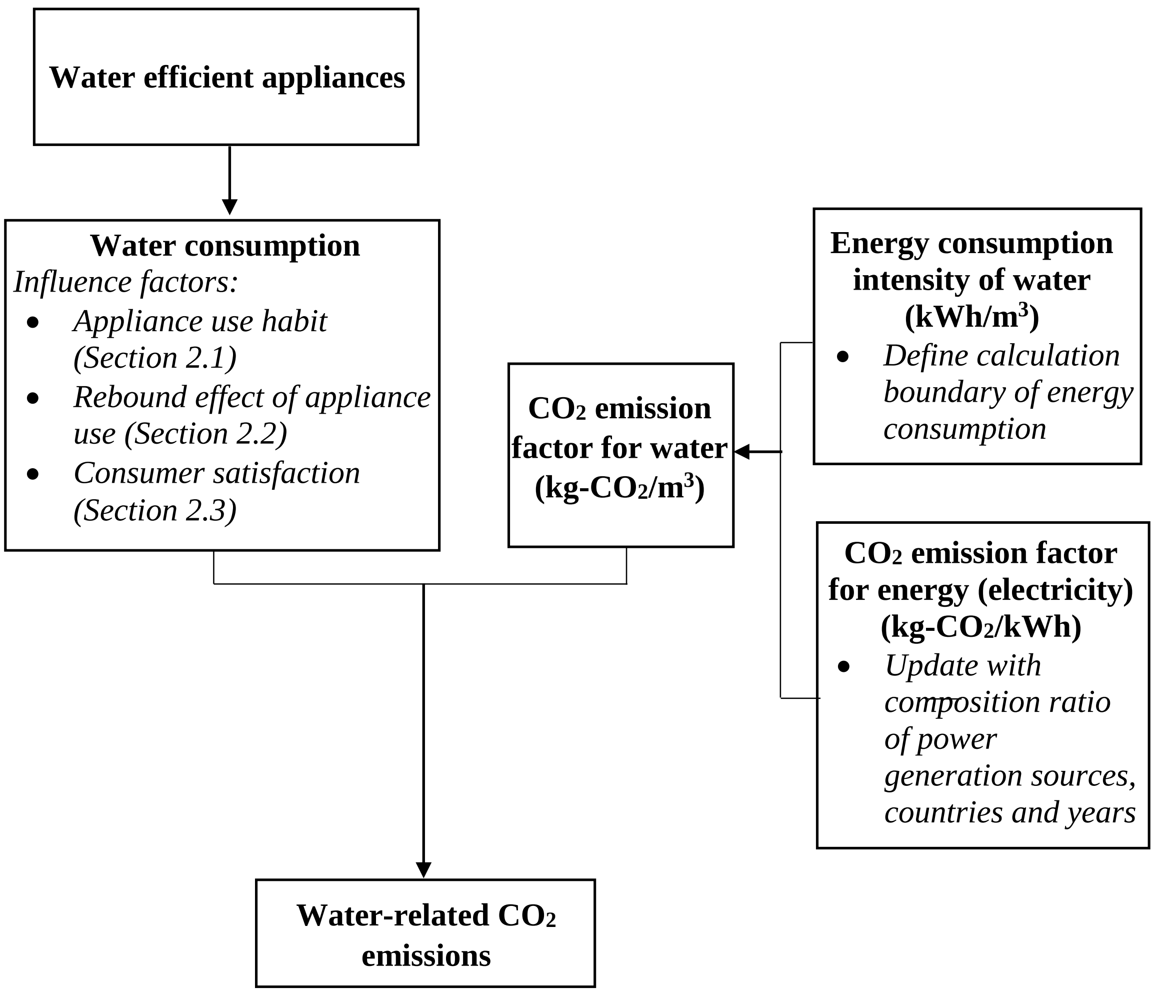



**Figure 2.2 Logic diagram for the calculation of $CO_2$ emissions from water use**

Hondo (2005) performed a life cycle analysis of greenhouse gas emission from power generation system, and greenhouse gas emission for nine different types of power generation systems were estimated. The results showed that the life cycle $CO_2$ emission factor for electricity (kg-$CO_2$ $kWh^{-1}$) varies with the types of power generation systems, e.g. the $CO_2$ emission factor was 0.975 kg-$CO_2$ $kWh^{-1}$ for coal-fired power generation, 0.741 kg-$CO_2$ $kWh^{-1}$ for oil-fired power generation, 0.608 kg-$CO_2$ $kWh^{-1}$ for liquefied natural gas-fired generation, 0.024 kg-$CO_2$ $kWh^{-1}$ for nuclear power generation, 0.011 kg-$CO_2$ $kWh^{-1}$ for hydropower generation, 0.015 kg-$CO_2$ $kWh^{-1}$ for geothermal power generation and 0.030 kg-$CO_2$ $kWh^{-1}$ for wind power generation. It was pointed out that the $CO_2$ emission factor for electricity changes with the composition ratio of power generation sources, and varies with countries and years (Cheng et al. 2012, Shimizu et al. 2012a). Therefore, the $CO_2$ emission factor for water should be updated correspondingly with the changes of $CO_2$ emission factor for electricity. Some reference values of $CO_2$ emission factor for electricity are as following: 0.376 kg-$CO_2$ $kWh^{-1}$ in Japan (Shimizu et al. 2012a), 1.11 kg-$CO_2$ $kWh^{-1}$ in China (Toyosada et al. 2012) and 0.475 kg-$CO_2$ $kWh^{-1}$ in Taiwan (Cheng et al. 2012).

### 2.2.1 Water consumption influence factor: habits

Specifically, shower habits are reviewed in this section. Questionnaire surveys showed that as Japanese like bathtub soaking bathing, they only took shower about 2.8-4.2 times in summer, and in winter, the times would further decrease (Hirose et al. 2013). While in Yarra Valley, Australia, it was reported that the average shower frequency was 0.76 showers per person per day (Robert 2005). Significant difference of shower frequency was shown in these two countries. Willis et al. (2013) pointed out that research of residential water consumption should be in specific country and location, as the community attitudes and behaviors, water stock efficiency profiles, environmental conditions, water pricing structures, government water restriction regimes and conservation message intensity vary in different countries or regions.

The shower duration time in Japan was 10.4-11.3 minute, in which longer shower duration time was in winter (Hirose et al. 2013). In Yarra Valley, Australia, average 7.1 minutes was taken for per shower (Robert 2005). As some people (about 85%) turn off showerhead while soaping, shampooing or doing other activities during shower (Lee et al. 2014), besides shower duration time, showerhead operating time is another critical parameter for the evaluation of shower water consumption. A survey study in Taiwan showed that showerhead operating time was 4.2 minutes (sd=1.5 minutes) when showerhead was turn off during soaping and shampooing, and 6.3 minutes (sd=1.6 minutes) were reported if showerhead was on during soaping and shampooing (Lee et al. 2014). Besides showerhead operating time, shower flow rate is another parameter for the evaluation of shower water consumption. In Taiwan, most people liked the showerhead with flow rate around 8-11 L $min^{-1}$ (Mean: 9.2 L $min^{-1}$, sd=1.3 L $min^{-1}$) (Lee et al. 2014). The mean flow rate across all showers in 840 households in Yarra Valley, Australia was 9.5 L $min^{-1}$ (Robert 2005).

### 2.2.2 Water consumption influence factor: rebound effect

Rebound effect of using water efficient appliances was raised in many previous studies (Campbell et al. 2004, Bennear et al. 2011, Price et al. 2014), e.g. actual water consumption reductions by water efficient appliances was less than the engineering estimates, which was due to the residents' behavior changes while using water efficient appliances. (Engineering estimates are calculated using the physical characteristics of water efficient appliances and typical behavior patterns, e.g. frequency of flushing, shower duration, loads of laundry per week (Price et al. 2014)) For example, residents may flush more than one time if water efficient toilets do not function to their satisfaction; or may extend shower time as reduced shower flow rate. The rebound effect was initially proposed for analysis of household adoption of energy efficient equipment, where it indicates the possible increase in consumption following a reduction in the effective price of energy services brought by energy efficiency improvements, and recent evidences seem to indicate that the rebound effect on energy use is limited (Millock and Nauges 2010). Bennear et al.'s (2011) study showed no evidence of rebound effect with installation of water efficient toilets, similarly no statistically significant evidence of rebound effect was found for water efficient appliances (including toilet, showerhead, washing machine, dishwasher) in Price et al.'s study (2014). However, significant rebound effect was reported by Davis (2008) for water efficient showerhead. Inconsistent results about rebound effects of using water efficient appliances were reported in these studies. More investigations about the rebound effects of using water efficient appliances are needed in the further in order to make the conclusions statistically convincible. As rebound effect is induced by behavior responses, detail investigation of residents' behavioral changes while using water efficient appliances is necessary for the study of rebound effect as well as its impact on water use.

The rebound effect of shower time with low flow showerheads have been investigated (Yamazaki et al. 2013, Lee et al. 2015). While using low flow showerheads, shorter showering time was reported when shower flow rate increased (Yamazaki et al. 2013). In Lee *et al*.'s (2015) study, compared with conventional showerheads, longer shower time was found when low flow showerheads were operating at low pressure, while the situation was reversed when operating at high pressure (Lee et al. 2015). The optimum flow rate of showering was proposed and defined as the flow rate felt 'optimum' by participants, and it showed that at optimal flow rate, even if the flow rate reduced after replacement by low flow showerheads, the shower time did not change (Toyosada et al. 2013). Besides, it was reported that comfort satisfaction of showerheads would decrease the shower time (Lee et al. 2015).

### 2.2.3 Water consumption influence factor: consumer satisfaction

Market performance of products in terms of consumer satisfaction and dissatisfaction is concerned by government, non-profit organizations and business, so that these organizations could enhance the product performance. Researches about consumer satisfaction of products emerged in 1970s and widely developed in past decades (Hunt 1976, Andreasen 1977, Westbrook 1980). The concept of consumer satisfaction/dissatisfaction is defined as the extent to which consumers' needs and wants are met (Hunt 1976).

Many researchers have used simple measures, most often single-item scales of four to seven points between the extremes of 'very satisfied' and 'very dissatisfied' to evaluate consumer satisfaction/dissatisfaction (Westbrook 1980). Some measures for evaluation of product satisfaction/dissatisfaction were reviewed by Westbrook (1980), and shown in Figure 2.3. The obvious advantage of single-item scales is that it is simple, however, single-item scales are still criticized on several aspects. First, if the single-item scale is used to evaluate the overall satisfaction of a product, it cannot provide information on components and cannot separately assess various dimensions, and thus may not entirely capture the complexity of consumer satisfaction (Zeithaml 1990). Second, variance due to a random error, a specific item, or a method factor cannot be assessed or averaged out, and it is difficult to assess the reliability of the measures (Zeithaml 1990). Third, single-scale measures commonly yield very skewed distributions of responses, suggests that the scales may be insufficiently sensitive to detect gradations of consumers' sentiments (Westbrook 1980). As an alternative, multi-item measures were proposed and researched.

Westbrook and Oliver (1981) compared five multi-item scales: verbal, graphic, Likert, semantic differential measures, in which semantic differential measures were reported having the highest reliability and convergent and discriminant validity (Zeithaml 1990). Compared with the single-item measures, multi-item measures were shown substantially reliable (Churchill and Surprenant 1982, Bearden and Teel 1983). For evaluations of consumer satisfaction, choosing a suitable measure(s) for a specific study is the guarantee of the evaluation results.

*(a) Single-item scales*

**Delighted-Terrible (D-T) scale:**

| 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|
| Delighted | Pleased | Mostly satisfied | Mixed (about equally satisfied and dissatisfied) | Mostly dissatisfied | Unhappy | Terrible |

**Percentage scale:**

| 100% | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0% |
|---|---|---|---|---|---|---|---|---|---|---|
| Completely satisfied | | | | | | | | | | Not at all satisfied |

**Satisfied-Dissatisfied (S-D) scale:**

| 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|
| Completely well | | | | | | Completely poorly |

*(b) Multi-item scales*

**Content analytic:**

Coding of free responses to a series of unstructured questions into the following categories:

1. Only unfavorable evaluations
2. Both favorable and unfavorable evaluations
3. Neither favorable nor unfavorable evaluations
4. Only favorable evaluations

**Figure 2.3 Measures for evaluation of product satisfaction/dissatisfaction**

**(Westbrook 1980)**

Lee and Tansel (2013) measured customer satisfaction of water efficient appliances in 64 households by a single-item rating scale of 6 points including ‘very dissatisfied’, ‘dissatisfied’, ‘neutral’, ‘satisfied’, ‘very satisfied’ and ‘uncertain’. The analysis results revealed that consumers’ satisfaction level of water efficient appliances was closely related to the actual water savings; the increase of satisfaction level would increase water savings from 5.36 to 8.39 gallons per household per day in the case (Lee and Tansel 2013). Lee et al. (2015) also reported that shower water demand was related to shower comfort satisfaction. These indicate that to evaluate water consumption by water efficient appliances, the aspect of consumer satisfaction should be considered. As consumer satisfaction and water consumption are both influenced by appliance attributes (taking showerhead as an example, like the water supply pressure and water flow rate), the correlations among consumer satisfaction, water consumption and appliance attributes need to be evaluated.

The relationship between shower attributes and shower comfort satisfaction reported by 10 Japanese were studied by Okamoto et al. (2013). It revealed that shower attributes including shower water distribution pattern, spray coverage and temperature drop influenced shower comfort satisfaction, while no influence was found of spray force (Okamoto et al. 2013). Chen and Lee (2016) reported that shower comfort satisfaction was related to the spray spread angle. Consumer preferred showerheads having characteristics of small spray angle, large water drop diameter, small spray coverage and hole number, and the optimum pressure preferred by consumer was around 50 kPa to 100 kPa (Chen and Lee 2016). Besides, it was reported that outdoor temperature influenced the satisfied shower water temperature (Lee et al. 2014). In all these studies, only descriptive relationships among shower comfort satisfaction, shower water consumption and shower attributes were given, no quantified correlations.

Mui and Wong (2006a, 2006b, 2007) proposed logistic regression models to correlate consumers' satisfaction with physical influence parameters while studying indoor aural/visual environment and indoor air quality. The models were built based on the analysis of cumulative frequency distribution and logistic regression of consumers' subjective responses measured by two assessment scales, namely semantic differential evaluation scale (from '0-Not acceptable' to '100-acceptable'; or five points from '-2 very bad' to '+2 very good') for indirect acceptability and dichotomous scale ('1-Acceptable' and '0-Not acceptable') for direct acceptability (Mui and Wong 2006a, Mui and Wong 2006b, Mui and Wong 2007). The expression of the logistic regression model is as Equation 2.1, where $\varphi$ is the probable satisfaction of consumers, $C_0$ and $C_1$ are the proportional constants of the regression equation, $\Phi$ is the influence parameter (Mui and Wong, 2007). As a reference, this method can be applied to quantify the correlations of consumers' satisfaction of water efficient appliance, e.g. showerhead, and appliance attributes in the future.

$$\varphi = \frac{\exp(C_0 + C_1\Phi)}{1 + \exp(C_0 + C_1\Phi)} \tag{2.1}$$

## 2.3 Evaluation aspect 2: Water supply system design

### 2.3.1 Probability theory

In hot and cold water installations, it rarely happens that all the appliances installed are in simultaneous use (The Institute of Plumbing 1988). The actual number in use, in relation to the total number capable of being used varies dependent on the occupational use in the various types of building (The Institute of Plumbing 2002), namely the water demand inside buildings is time variant.

Smart water metering technologies were applied to collect empirical evidence of when and which water end use event (such as in showers, toilets, clothes washers, garden irrigation, etc.) was occurring in household (Stewart et al. 2010, Bleys et al. 2012, Vrana et al. 2016). Data reading from smart metering instruments were used for investigation of household water consumption patterns (Stewart et al. 2010, Beal et al. 2012). As the study of water consumption end use by Willis et al. (2013), a higher resolution water meter with data logging equipment which allows for continuous water consumption recording was installed in 151 homes across Gold Coast City, Australia. Besides, stock appliance audits (i.e. type and characteristics of each household appliance or fixture) were used to help identify flow trace patterns for each household (Willis et al. 2013).

Besides smart water metering, water consumption end use can also be estimated by the application of probability theory. Over the last decades, probability theory has been widely applied in estimating water demand and determining design flow rate since the application by Hunter in 1940 (Hunter 1940, Wise and Swaffield 2002).

The probability that $r$ out of $n$ fixtures will be operating at a particular instant of observation was defined as Equation 2.2 (Hunter 1940), in which the probability that a particular fixture out of a number, $n$, will be found operating at any arbitrarily chosen instant of observation is $t/T$, where $t$ has been defined as the duration of each operation and $T$ as the time between operations of each fixture.

$$p_r^n = C_r^n \left(\frac{t}{T}\right)^r \left(\frac{T-t}{T}\right)^{n-r} = C_r^n \frac{t^r (T-t)^{n-r}}{T^n} \tag{2.2}$$

In order to accurately estimate simultaneous water demand, these factors including capacity of appliance, draw-off flow rate, draw-off period and use frequency, should be taken into account when using probability theory (The Institute of Plumbing 2002). Therefore, establishing the distributions of capacity of appliance, draw-off flow rate, draw-off period and use frequency for different kinds of appliances in different types of buildings is needed.

Simultaneous water demand by one type of appliance can be estimated properly by using probability theory. However, when applying the probability theory to several different types of appliances, overestimation of water demand was found. Hunter (1940) pointed out that the principal reason for the overestimation does not lie in any inherent fault in the probability function, but in that the application of the method does not consider the probability, or rather the improbability, of overlapping between or among two or more groups of different types of appliances. It was also pointed out that the details of application of any method in practice must be guided to a large extent by engineering judgement in order that it may lead to satisfactory results (Hunter 1940). Determining the empirical evidences about overlapping distribution among different types of appliances is necessary for improving the estimation accuracy by probability theory in the future.

It should be noted that the use of probability theory in assessing simultaneous water demand is only applicable where large numbers of sanitary fittings are involved, as probability theory is based on the likelihood of situations occurring and therefore its predictions will be exceeded on rare occasions (CIBSE Guide G 2004). In practice, high-rising buildings with large plumbing systems that feed large amount of appliances will be an appropriate target for the application of probability theory in assessing simultaneous water demand.

### 2.3.2 Murakawa's simulation for water consumption (MSWC)

Monte Carlo method has been widely used to dynamically predict water consumptions in kinds of buildings by Murakawa et al. (Murakawa and Takata 2002, Murakawa et al. 2015, Takata et al. 2015). The Monte Carlo simulations conducted by Murakawa et al. were based on a load calculation model which was developed according to the appliance usage in the time series through a day, consisting of average values and distributions of appliance usage frequency, number of usages, duration time of usage and discharge flow rate (Murakawa and Takata, 2002). The calculation procedures for water consumption loads are shown in Figure 2.4 (Murakawa and Takata 2003).

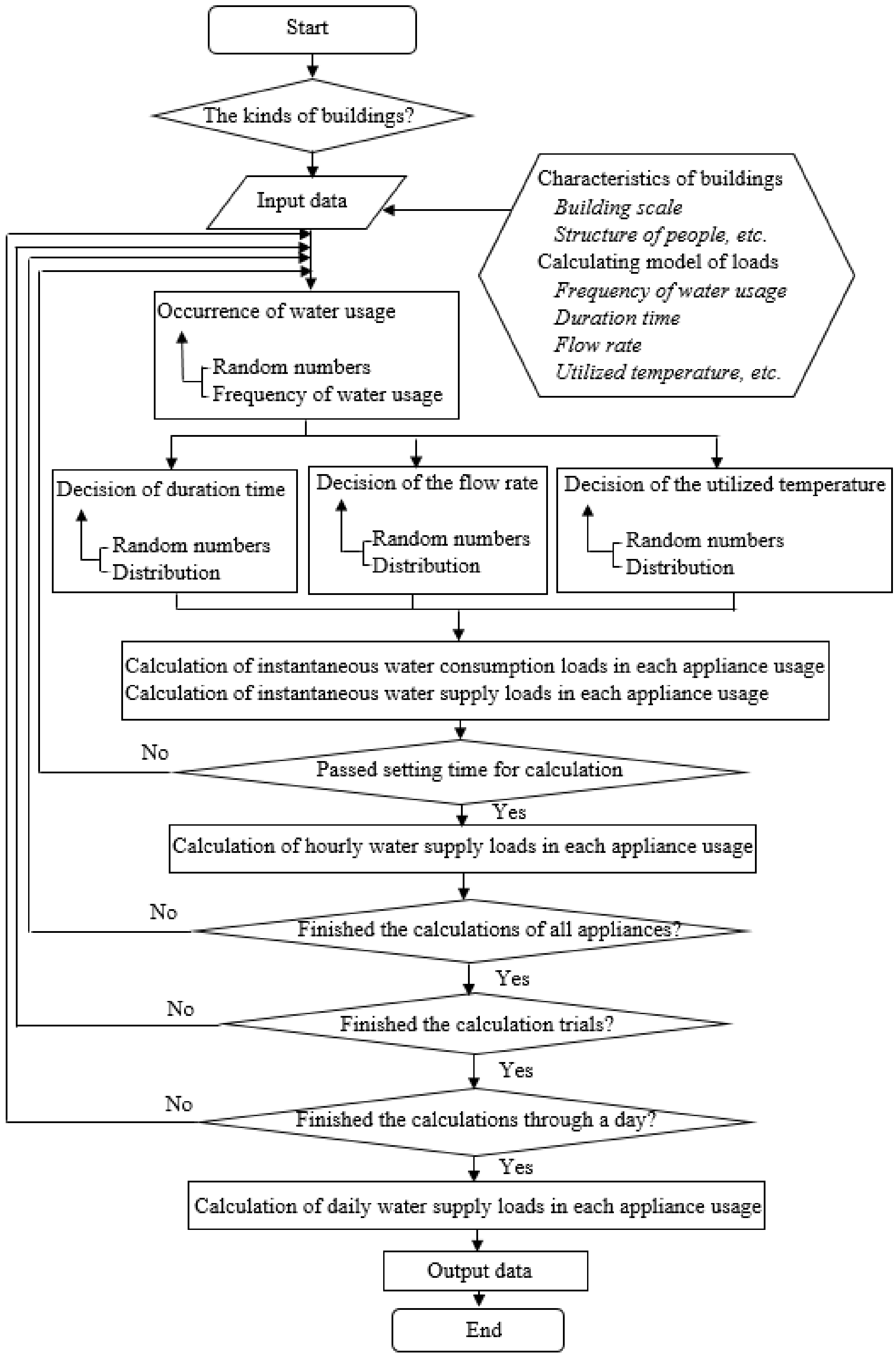



**Figure 2.4 Procedures for calculation of cold and hot water consumption loads**

**(Murakawa and Takata 2003)**

In Murakawa's simulation, building characteristics (taking apartment house as an example, including number of households, family size, life style, schedule of going out, number of appliances and types of appliances) were investigated before calculation (Murakawa and Takata 2002). All these characteristics are helpful for the determination of water consumption pattern in the building. The setting of the calculation model in Murakawa's simulation was based on detail investigation of water usage in buildings (Murakawa and Takata 2002). The water usage of each appliance was simulated according to the occurrence of random numbers based on the distributions of water usage, including occurrence time interval of water usage, the duration of water usage and the discharge flow rate in each water usage (Murakawa and Takata 2003). The pseudo-random numbers were generated by personal computer (Murakawa and Takata 2003), and were used to simulate the random usage of appliances.

According to above descriptions, three key steps can be summarized when using Monte Carlo method to estimate water consumption, as following:

- Define a problem of random appliance usage in a time series through a day, then developing a corresponding mathematical model for this random problem;
- Use pre-generated random number to sample occurrence time interval of water usage, the duration of water usage and the discharge flow rate in each water usage from existing distributions of these factors for the parameter setting of the model. The distributions were built based on investigations of actual water usage in buildings.
- Run Monte Carlo simulation.

Two calculation models were proposed by Murakawa et al., namely 'each fixture usage model' and 'flat unit model' (Murakawa and Takata 2002, Murakawa and Takata 2003). For each fixture usage model, water demand in the whole building was acquired by simulation of water usage by each appliance (water usage by different types of appliances was simulated simultaneously) (Murakawa and Takata 2002, Murakawa and Takata 2003). For flat unit model, water usage by each appliance in a flat unit was set as a unit, then water demand in the whole building was obtained by simulation of water usage by each flat unit (Murakawa and Takata 2002, Murakawa and Takata 2003). The calculation models in the Murakawa's simulations were validated by comparing the predicted average water consumption per day at target buildings and reading data from water meter installed in the buildings (Wu et al. 2013, Wu et al. 2014, Wu et al. 2015). Although the predicted water consumption by Murakawa's simulations was closer to the measured water consumption in the building when compared with that calculated by methods in design criteria, the predicted results were still overestimated (overestimation of 36-74% for whole building water demand). Discharge overlapping among different types of appliances is the main factor that compromises the simulation accuracy. However, no detail definition of discharge overlapping was found in Murakawa's each fixture usage model and flat unit model while simulating water consumption by different types of appliances. The simulated result of water demand by existing Murakawa's models can be calibrated by deducting the overestimation percentage (36-74%). However, the overestimation percentage changes for different water supply systems in different buildings. Modifying the model that considering the discharge overlapping among different types of appliances is needed for more accurate simulation of water demand in buildings. Including factors that reflect discharge overlapping among different types of appliances into the calculation model will be a choice for the improvement of estimation accuracy, but it is difficult in practice. As an alternative, water use by each type of appliances can be simulated separately by Monte Carlo method first, then the separate simulation results of each type of appliances can be summed up along the time series. As the simulation of water use by each type of appliances is based on the field-surveyed water demand pattern, the discharge overlapping among different types of appliances can be avoided during the summation process.

Simultaneous water demand along the time series of 24 hours were given by the Murakawa's simulations (Murakawa and Takata, 2002, Murakawa and Takata 2003, Wu et al. 2013, Murakawa et al. 2015, Takata et al. 2015), and the maximum simultaneous demands were determined from the water demand time series. The maximum simultaneous water demand can be taken as the probable maximum inflow rate of pumping system like the practices in some design standards/guidelines (The Institute of Plumbing 2002, CEN 2006). However, as the maximum simultaneous water demand usually last for a short period in a day, it may be not an optimal solution to take maximum simultaneous water demand as the design flow rate of pumping system (Wong et al. 2014a). For buildings with roof tank water supply systems, roof tank influences the water demand-and-recovery balance in the pumping system and suggested to be taken into account when determining the design flow rate.

### 2.3.3 Design flow rate according to standards/guidelines

The empirical loading unit methods which were based on probability theory have been used in various codes for determination of design flow rate (Wise and Swaffield 2002), like Plumbing Engineering Services Design Guide (The Institute of Plumbing 1988), CIBSE Guide G (2004), and European Standard EN 806-3:2006 (CEN 2006). Beginning at the last draw-off point, the loading units for each section of the installation have to be determined and added, and the design maximum flow rate can be determined from pipe sizing charts (The Institute of Plumbing 2002, CEN 2006).

Several studies revealed that the calculated maximum flow rates by standards/guidelines were overestimated (Bleys et al. 2012, Vrana et al. 2016). The maximum flow rates calculated according to German standard DIN 1988-3, European standard EN 806-3, French specification DTU 60.11 and Dutch guideline ISSO 55 were compared with the measured peak flow rates in a number of apartment buildings in Belgium during 2011-2012, it revealed that existing standards/guidelines overestimate the peak flow rate by 2 to 3 times (Bleys et al. 2012). Similar study was conducted by Vrana et al. (2016). Maximum flow rates in 10 residential buildings in Czech Republic were measured with data logging of each second, and compared with design flow rates established according to different standards, like the Czech Standard CSN 75 5455, Slovak Standard STN 73 6655, Swiss instructions W3 and German Standard DIN 1988-300 (Vrana et al. 2016). It showed that the measured maximum flow rates in all buildings were lower than design flow rates determined by these standards; the difference between the measured peak flow rate and the design flow rate based on CSN 75 5445 and STN 73 6655 was largest, while the difference between the measured peak flow rate and the design one determined by Swiss instructions W3 and German Standard DIN 1988-300 was smaller (Vrana et al. 2016).

Bleys et al.' (2012) study also revealed that measurement interval has an important impact on the measured maximum flow rate: measurement interval up to 5 seconds had no significant influence on the measured maximum flow rate; from 10 seconds onwards the measured maximum flow rate decreased while increasing measurement interval. Measurement over an interval of 15 minutes for instance, would underestimate the domestic hot water peak flow rate by 35% and the domestic total water maximum flow rate by 57% (Bleys et al. 2012).

### 2.3.4 Occupant load and water demand pattern in high-rise buildings in Hong Kong

As shown in Figure 2.4, the simulation accuracy of water demand by Monte Carlo method is highly dependent on the input parameter values (i.e. occupant load, water demand pattern) that derived from field survey. The occupant load and water demand pattern in high-rise buildings were studied by Wong and Mui via two interview surveys in residential households in Hong Kong (Wong 2003, Wong and Mui 2004a, Wong and Mui 2004b, Wong and Mui 2007a, Wong and Mui 2007b).

The first interview survey was carried out in 43 households of a typical old high-rising residential building in Hong Kong in 2003, which only focused on the occupancy number (Wong 2003). The representative of each household was asked to identify the usual occupancy patterns in the household throughout the day in the specified time period and the number of occupants living in the household (Wong 2003). The second face-to-face interview survey was performed in 597 selected households of 14 high-rising residential buildings in Hong Kong in late 2003-2004 (Wong and Mui 2004a, Wong and Mui 2004b, Wong and Mui 2007a, Wong et al. 2010). Most of the interviewees were occupants who stayed at home for the longest time every day. The occupant load variation during a day throughout a week were surveyed (Wong and Mui 2004a, Wong and Mui 2004b, Wong and Mui 2007a). Besides, the usage pattern of the day prior to the interview and the hourly usage patterns in 24-hour basis on weekdays, weekend, Sunday and holiday with the corresponding activities were asked (Wong and Mui 2004a, Wong and Mui 2004b, Wong and Mui 2007a). The average time between appliance demands was surveyed and the appliance type, physical size and the brand name were recorded (Wong and Mui 2004, Wong and Mui 2004b, Wong and Mui 2007a).

The second survey reported that the average number of occupant per household is 4.2 (Wong and Mui 2004a, Wong and Mui 2004b, Wong and Mui 2007a). The occupant load variation factor was defined as the occupant load at a time as a percentage of the maximum occupant load (Mui and Wong 2012). The occupant load variation factor obtained from the two interview surveys is shown in Figure 2.5 (Wong et al. 2014a, Wong et al. 2017). It can be seen from Figure 2.5, the occupant load in the morning and at night is high, while in the daytime, the occupant load is low, which agrees with the real situation.

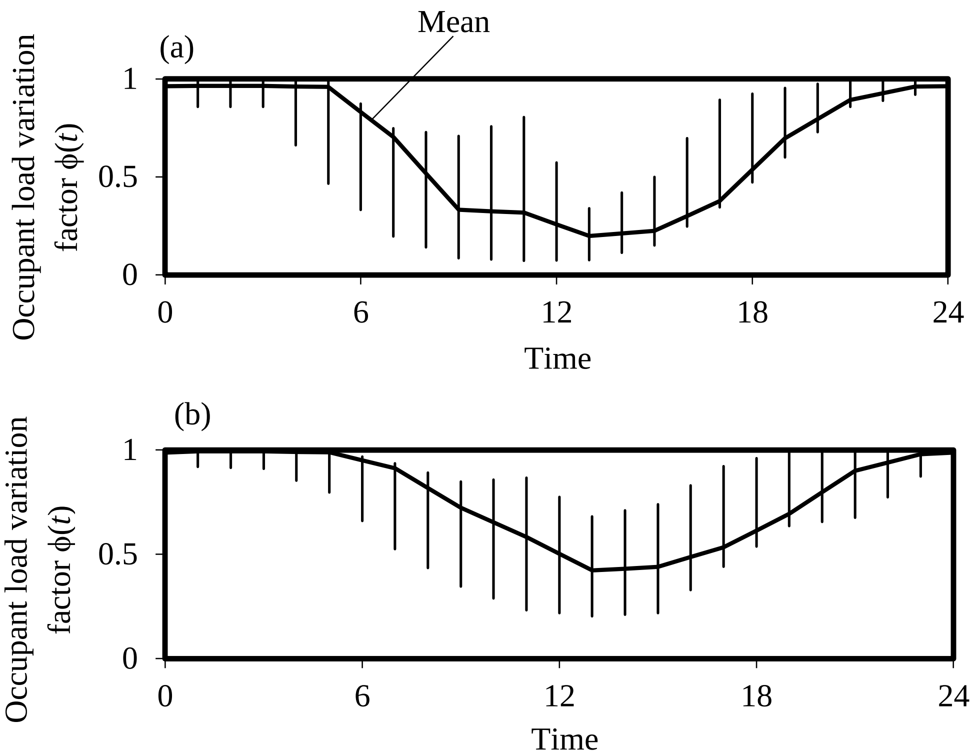



**Figure 2.5 Occupant load variation factor γ(*t*): (a) weekdays; (b) holidays**

According to the second survey, all occupants would take at least one shower per day (Wong et al. 2010). Among the 597 interviewees, 269, 289, 37 and 2 of them would take one, two, three and four showers in the summer while 537, 57, 3 and none of them would take one, two, three and four showers in the winter respectively (Wong et al. 2010). On average, an occupant would take 1.6 (standard deviation (SD)=0.6) showers on a summer day (June-August) and 1.1 (SD=0.3) showers on a winter day (December-February), giving an overall average of 1.4 (SD=0.6) showers per day (Wong et al. 2010). Besides, it was reported that all the winter showers and 97% summer shower were hot water ones, which the hot water heater was operated (Wong et al. 2010). The geometric average of the discharge time of a shower operation was 12 minutes (=720 s) with a geometric standard deviation of 1.6 minutes (=96 s). The distribution of discharge time of a shower operation was shown in Figure 2.6 (Wong et al. 2010). Comparatively, another domestic water consumption survey conducted by HKWSD (Hong Kong Water Supplies Department) in 2011 (September 2011-January 2012) showed that the household average daily per capita frequency of showering was 1.04 times and the duration per shower was 6.7 minutes (=402 s) in average (Hong Kong Water Supplies Department 2011b). The review results are summarized in Table 2.2. A significant difference (difference of 44 %) of the showerhead operating time is found between the two surveys. In Wong et al.'s (2010) survey, it lasted for a long period, which covers the winter time; while the survey by HKWSD (2011b) only covers the time from September 2011 to January 2012, the showering characteristics in winter are not reflected by the survey. This may be the reason for the significant difference of the showerhead operating time by the two surveys.

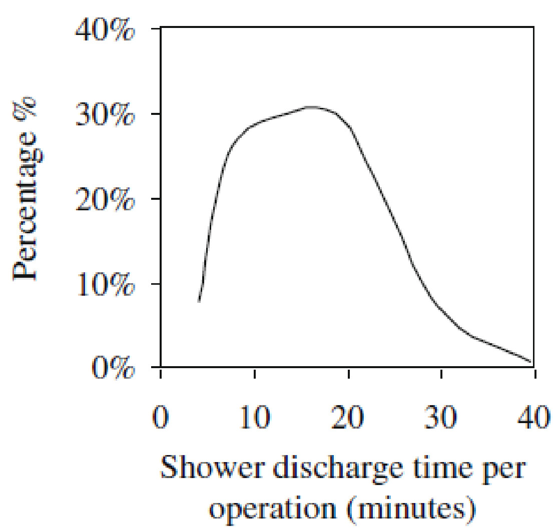



**Figure 2.6 Shower discharge time of each operation (Wong et al. 2010)**

**Table 2.2 Summary of field-surveyed shower demand patterns**

| Parameter | Values | Distribution | Reference |
|---|---|---|---|
| Number of showers per resident per day, $N_i$ ($hd^{-1}d^{-1}$) | range=1-3, mean=1.6 (Jun-Aug) | Discrete | Wong et al. (2010) |
| | range=1-3, mean=1.1 (Sep-May) | Discrete | Wong et al. (2010) |
| | mean=1.04 (Sep-Jan) | Discrete | Hong Kong Water Supplies Department (2011b) |
| Showerhead operating time, $t_s$ (s) | mean=402, CI=178-910 | Log-normal | Hong Kong Water Supplies Department (2011b) |
| | mean=720, SD=96 | Log-normal | Wong et al. (2010) |
| Hot showers, $\phi$ | 97% (Jun-Aug) | Discrete | Wong et al. (2010) |
| | 100% (Sep-May) | Discrete | Wong et al. (2010) |

Note: SD = standard deviation; CI=99% confidence interval

The second survey provides the per-person hourly demand pattern of each type of appliances throughout a day, including showerheads, wash basins, kitchen sinks and washing machines, as shown in Figure 2.7. Besides, the hourly demand patterns of each type of appliances in an apartment are also provided, as shown Figure 2.8. As shown in Figures 2.7 and 2.8, obvious night demand peaks for all these types of appliances were found, comparatively, morning demand peaks were also detected but unobvious for some types of appliances, such as showerhead.

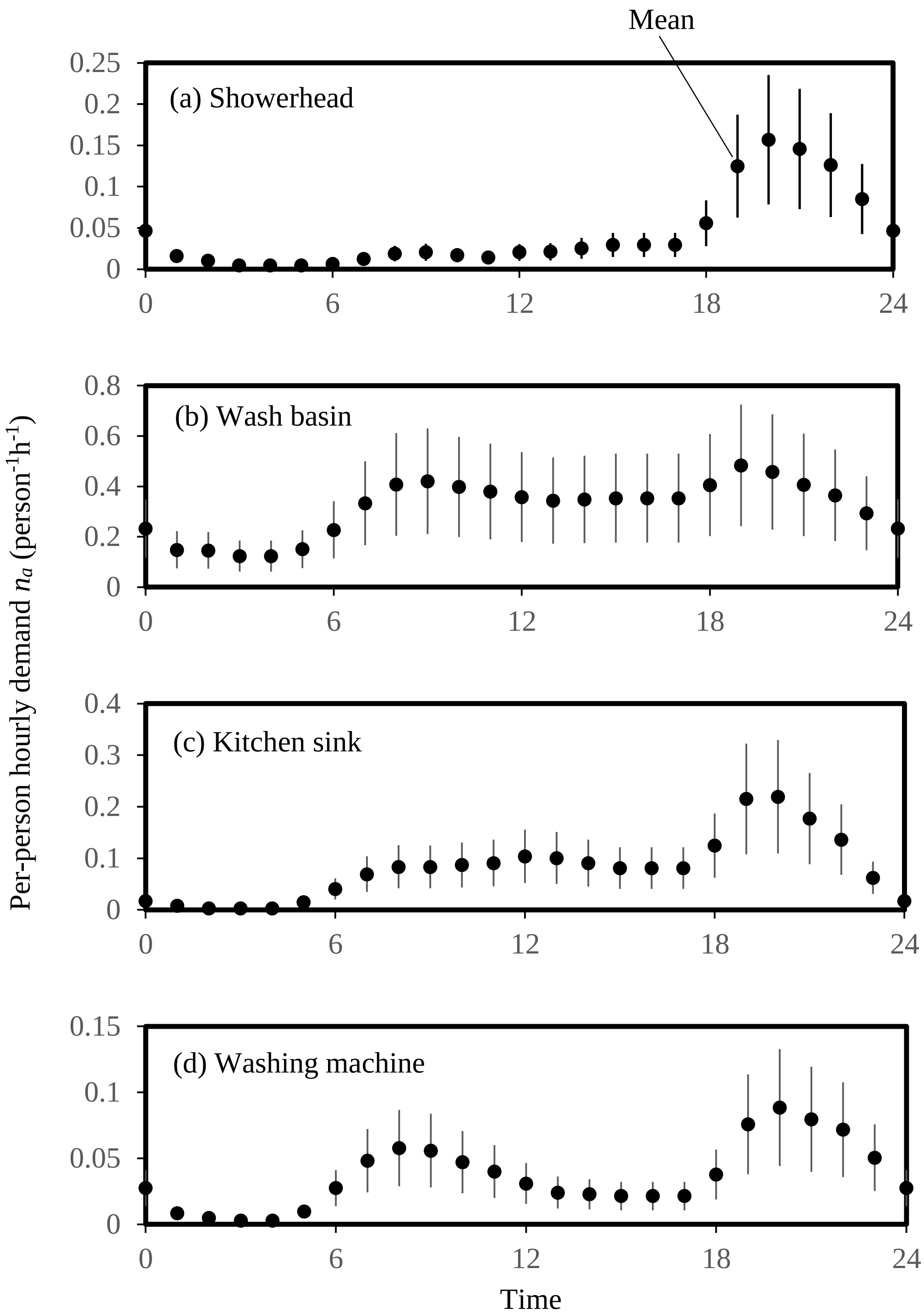



**Figure 2.7 Per-person hourly demand $n_a$: (a) showerhead; (b) wash basin; (c) kitchen sink; (d) washing machine**

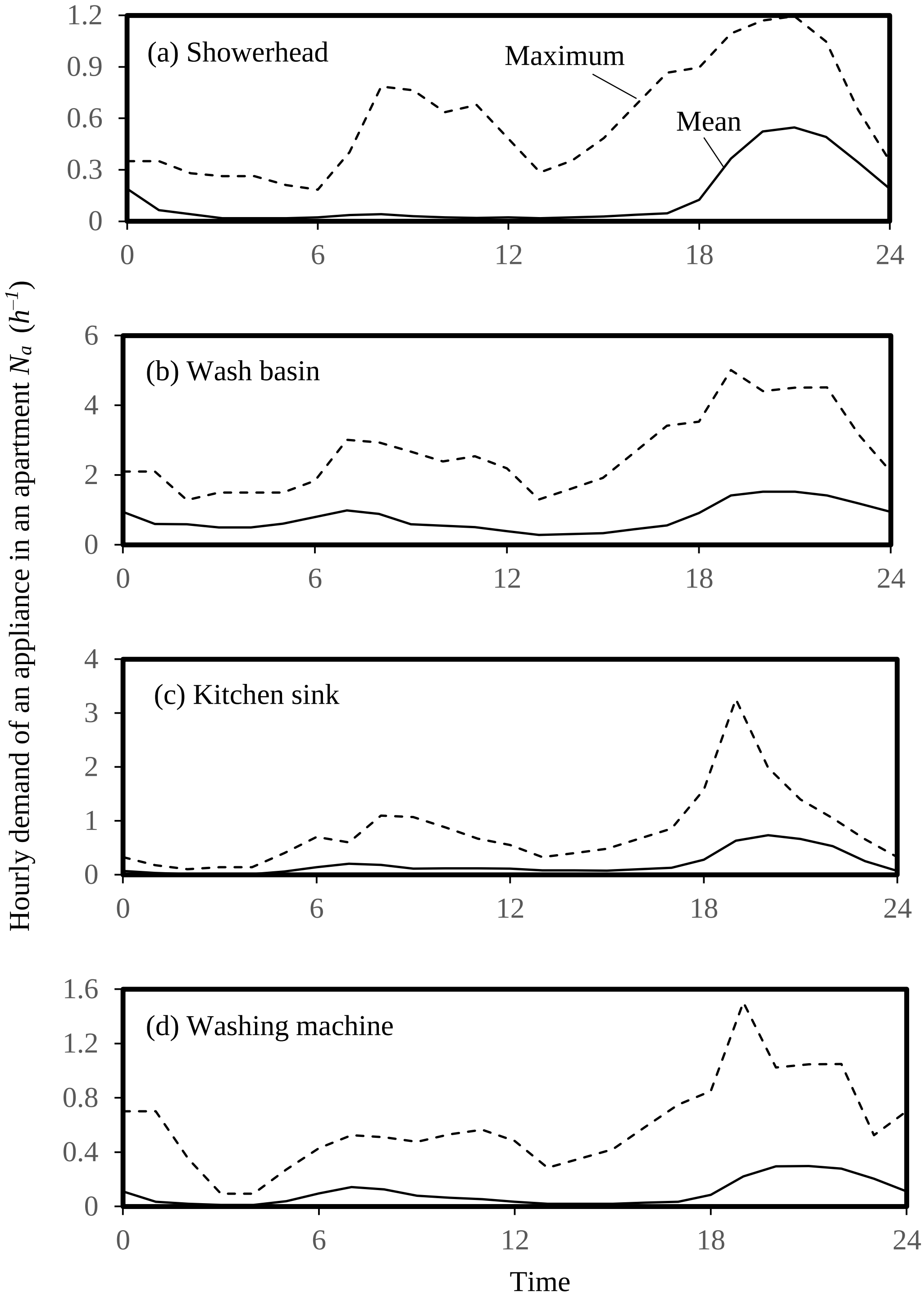
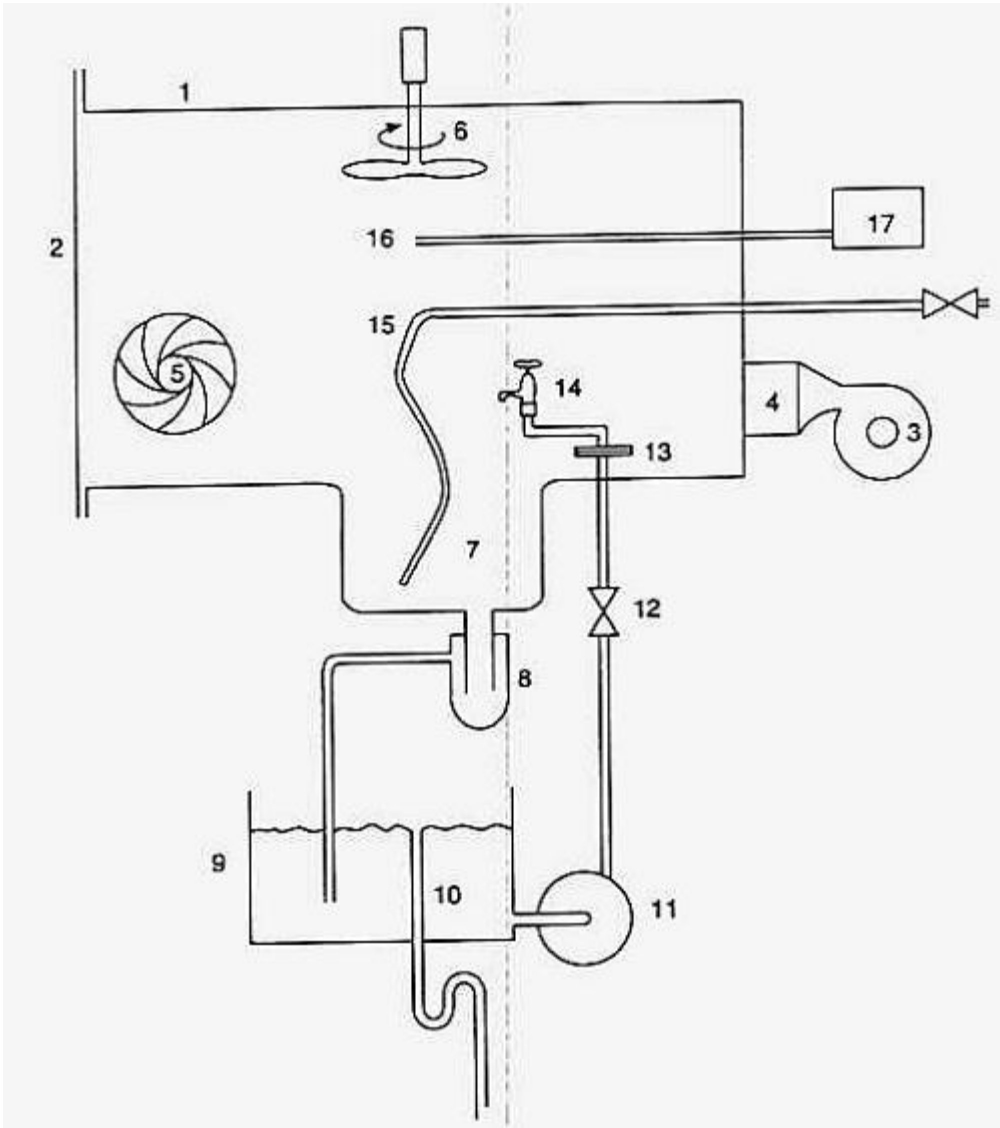



**Figure 2.8 Hourly demand of each type of appliances in an apartment: (a) showerhead; (b) wash basin; (c) kitchen sink; (d) washing machine**

## 2.4 Evaluation aspect 3: Aerosol generation of water consuming appliances

Experimental methods were widely used to assess the aerosol generation by water consuming appliances in previous studies (Carson 1996, Cowen and Ollison 2006, Zhou et al. 2007, O’Toole et al. 2009), as summarized in Table 2.3. Carson (1996) used one mechanically ventilated test chamber (chamber 1.53×0.84×0.835m; with a water sink 0.4×0.33×0.17m) with tap/showerhead discharging inside for the experimental study of aerosol generation, as shown in Figure 2.9. In Cowen and Ollison’s (2006), Zhou et al.’s (2007) and O’Toole et al.’s (2009) works about showerhead aerosol generation, showerhead discharging tests were performed in bathroom or shower stall, and with a full-size mannequin inside; shower spray was hit on the chest or the neck back of the mannequin to simulate the splashing effect. Zhou et al.’s (2007) experimental setup is shown in Figure 2.10. Compared with full-size bathroom or shower stall, the experimental conditions, such as ventilation rate and relative humidity, in test chamber can be controlled easily. However, electrostatic effect in test chamber should be payed attention to. Electrostatic effect can be caused by metal and plastic materials of chamber, which would accelerate the aerosol deposition on chamber walls and further influence the monitored aerosol concentration in the space. Chamber materials without electrostatic effect, such as glass, are suggested for the chamber studies of aerosol generation of water consuming appliances. Shower sprays hitting on mannequin can simulate the water splashing effect, but also make it difficult to control the experimental conditions. As the hitting point and hitting angle of shower spray on mannequin would influence the splashing effect, and further influence the aerosol generation. Stricter control of experimental conditions about mannequin is needed.




1. Glove Box 1.53×0.84×0.935 m, 1.202 $m^3$
2. Removable end for access
3. Variable speed fan: air supply
4. HEPS filter
5. Iris damper fitted to glove port as air outlet
6. Air stirrer with external motor
7. Sink 0.4×0.33×0.17 m, 0.022 $m^3$
8. Bottle trap
9. Reservoir tank
10. Overflow plug to drain
11. Variable speed water pump
12. Quick action valve
13. Water filter (pore size 0.45μm)
14. Tap being tested
15. Mains water supply with flexible delivery pipe
16. Air sampling probe
17. Airborne particle counter

**Figure 2.9 Schematic diagram of experimental apparatus in Carson's (1996) study**

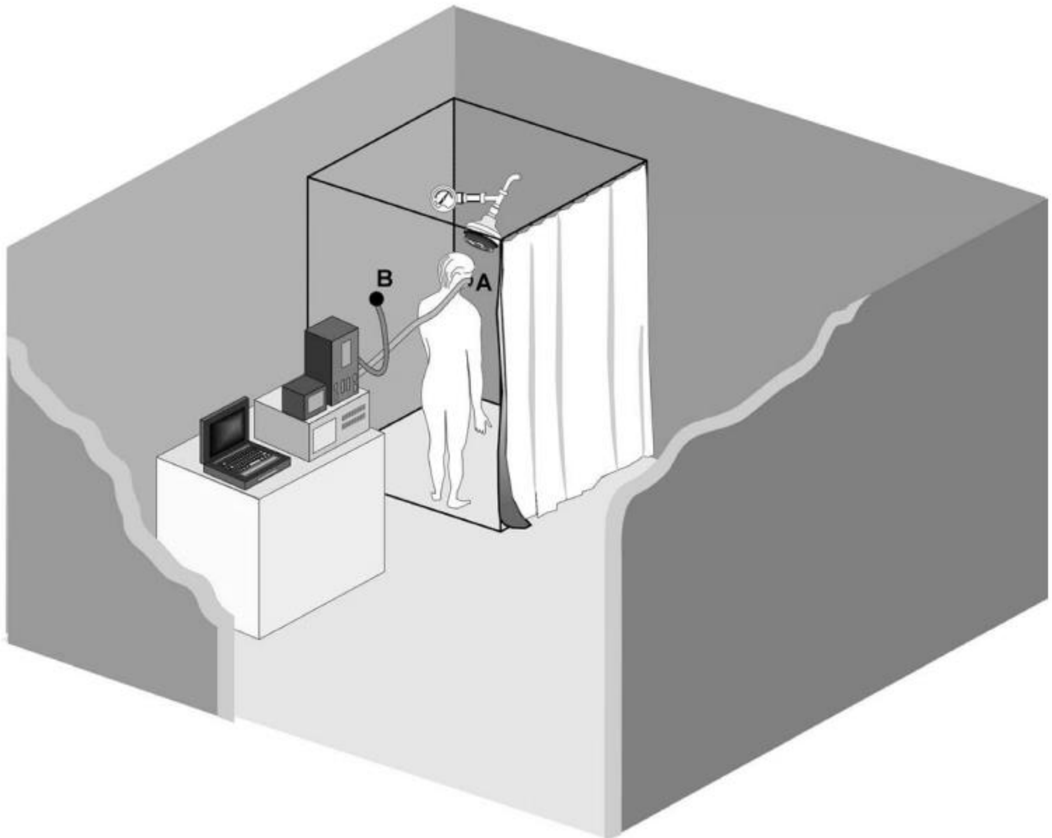



**Figure 2.10 Schematic of the experimental set-up in Zhou et al.'s (2007) study**

In these experimental studies, aerosols generated by discharging taps or showerheads were sampled and analyzed by existing instruments. For the earlier study by Bollin et al. (1985), an Andersen 1 AFCM viable (microbial) particle sizing sampler (Andersen Samplers, Inc., Atlanta, Ga.) which consisted of six round aluminum stages clamped together to form a sealed cylinder was used for aerosol collection. Air vents on the stages became progressively smaller as stages progressed from top (1.51 mm, stage 1) to bottom (0.25 mm, stage 6) (Bollin et al. 1985). In Carson's (1996) study, a light scattering counter was placed in the middle of the chamber for the measurement of aerosol concentration.

Zhou et al. (2007) placed DataRAM (random-access memory) real-time particle monitor (Monitoring Instruments for the Environment, Inc., Bedford, MA) and Aerodynamic Particle Sizer (APS 3310; TSI, Inc., Amherst, MA) at the height of mannequin's breathing zone to measure aerosol mass concentration, and particle size and mass size distributions respectively. Concentrations of aerosols in different size range were measured by three separate equipment in O'Toole et al.' (2009) experimental study, namely Aerodynamic Particle Sizer (measurement size range of 500 nm to 5 μm), Scanning Mobility Particle Sizer (measurement size range of 15 nm to 700 nm), and Phase Doppler Particle Analyzer (measurement size range of 500 nm to 250 μm). Only using one instrument, duplicate CI-500 particle monitors (Climet Instruments CO.), by Cowen and Ollison (2006), particle concentrations in six size fractions (0.3-0.5, 0.5-1, 1-2.5, 2.5-5, 5-10, and >10μm) were determined. Although these instruments can measure the aerosol concentration or aerosol size conveniently, still some errors may be caused while using these existing instruments. As these instruments measured liquid aerosols, especially alkaline liquid, such as salt water aerosols, corrosions of sensors in the instruments may be caused, which would influence the measurement accuracy especially after a long period of measurement.

Aerosol mass or number balance equations which include terms of aerosol concentration and aerosol generation rate were defined in enclosure spaces, i.e. test chamber or shower stall, in Carson's (1996), Cowen and Ollison's (2006) and Zhou et al.'s (2007) studies. Based on the measured aerosol concentrations, the aerosol generation rates of taps or showerheads were acquired by the aerosol balance equations. The forms of aerosol balance equations in Carson's (1996), Cowen and Ollison's (2006) and Zhou et al.'s (2007) studies were similar. Taking Carson's (1996) study for example, perfect mixing of air in the chamber was assumed and the form of the aerosol number balance equation was as Equation 2.3, where $N_t$ (number of particles m$^{-3}$) was the aerosol concentration at time $t$, $n$ (number of particles s$^{-1}$) was the release rate of aerosols, $Q$ (m$^3$ s$^{-1}$) was the ventilation rate, $V$ (m$^3$) was the enclosure volume, $t$ (s) was the time from start of aerosol release.

$$N_t = \frac{n}{Q}\left[1 - e^{-\left(\frac{Qt}{V}\right)}\right] \tag{2.3}$$

As shown in Equation 2.3, the aerosol loss caused by ventilation was included in the aerosol balance equation, while the aerosol deposition on chamber walls was not included, which caused the calculated aerosol generation rate less than the actual value. For the mass balance equation in Cowen and Ollison's (2006) study, the term of first-order rate of decay was defined, but no specification about the cause of the decay. In Zhou et al.'s (2007) work, specific description of the first-order rate of decay was given; the aerosol loss was caused by the ventilation and the aerosol deposition on shower walls, floor and mannequin body, in which the aerosol deposition rate on shower walls was calculated based on mathematical expression given by Crump and Seinfeld (1981). In the result, only the total decay rate of aerosols was given, not specifying the value of the aerosol deposition rate. Using the same aerosol loss rate equation given by Crump and Seinfeld (1981), the experimental study by Zhou and Cheng (2000) showed that in a vessel of volume about 106 m$^3$ with air exchange rate ranged from 1 to 3.6 h$^{-1}$, the aerosol loss caused by aerosol deposition on walls was much smaller than that caused by ventilation when particle size was below 2.5μm. Determining the aerosol deposition rate is necessary for the accurate estimation of aerosol generation rate by aerosol balance equations. Except experimental methods, computational fluid dynamics (CFD) simulation can be an alternative method for the study of aerosol deposition in the future, which has been used in many previous studies about indoor particulate contaminants (Lu and Howarth 1996, Zhao et al. 2004, Chang et al. 2006). Previous computational results revealed that indoor particulate concentration, distribution and deposition were related to the specific particulate properties, ventilation conditions and room dimensions. It is the same situation for aerosols in test chambers or shower stalls.

Considering the safety, salt was usually used to replace Legionella bacteria for experimental studies of aerosolized Legionella bacteria from water consuming appliances. Carson (1996) demonstrated that the use of salt to simulate the particulate Legionella may have effect on aerosol generation, but the effect was not significant. Cowen and Ollison's (2006) study showed that introduction of salt solutions into the source water increased particle formation rates for size fractions < 10 μm, however, little apparent change in particle concentration for particles above 10 μm in size. It was also pointed out that although salt content in water did has an influence on fine particle formation, the relationship was not linear over the tested total dissolved solids levels (Cowen and Ollison 2006).

**Table 2.3 Summary of studies about aerosol generation by taps/showerheads**

| Study | Experimental condition | Aerosol sampling equipment | Proposed aerosol balance equation | Aerosol generation rate | Remark of Water that supplied to tap/showerhead |
|---|---|---|---|---|---|
| Carson (1996) | One mechanically ventilated test chamber (chamber 1.53×0.84×0.835m; with a water sink 0.4×0.33×0.17m) with tap/showerhead discharging inside it | A light scattering counter to measure aerosol concentration | $N_t = \frac{n}{Q}\left[1 - e^{-\left(\frac{Qt}{V}\right)}\right]$<br>$N_t$ — aerosol concentration at time $t$ (number of particles/m$^3$);<br>$n$ — release rate of aerosols (number of particles/s);<br>$Q$ — ventilation rate (m$^3$ s$^{-1}$);<br>$V$ — enclosure volume (m$^3$);<br>$t$ — time from start of aerosol release (s) | $2.34\times10^5$ particles s$^{-1}$ | Salt water was used for the experiment |

**Table 2.3 Continued**

| Study | Experimental condition | Aerosol sampling equipment | Proposed aerosol balance equation | Aerosol generation rate | Remark of Water that supplied to tap/showerhead |
|---|---|---|---|---|---|
| Cowen and Ollison (2006) | **(1)** Test runs were performed in a residential bathroom (~11m3); **(2)** Ventilation in the bathrooms included a ceiling exhaust fan and an air vent connected to the house heating, ventilating, and air conditioning (HVAC) system; **(3)** A full-size mannequin was positioned in the shower spray cone to simulate splashing | Duplicate CI-500 particle monitors (Climet Instruments Co.) were used to measure the particle concentrations in six size fractions (0.3-0.5, 0.5-1, 1-2.5, 2.5-5, 5-10, and >10 μm) | $N(t)=\frac{R}{\lambda}\left(1-e^{-\lambda t}\right)$ *N(t)* — the particle concentration at time *t*; *R* — the formation rate of particles; *λ* — the first-order rate of decay, including removal by air exchange, deposition, and shower cone interactions; *R/λ* — the steady state particle concentration approached after long showers | 4-41.3 μg $m^{-3}$ $min^{-1}$ | A concentrated Epsom salt ($MgSO_4.7\ H_2O$) solution was injected into the water flow |

**Table 2.3 Continued**

| Study | Experimental condition | Aerosol sampling equipment | Proposed aerosol balance equation | Aerosol generation rate | Remark of Water that supplied to tap/showerhead |
|---|---|---|---|---|---|
| Zhou et al. (2007) | **(1)** Aerosols were generated within a shower stall (0.92×0.92×2.41m, placed in a bathroom having dimensions of 3.75×1.85×2.4m) containing a mannequin (1.70m high) to simulate the presence of a human; **(2)** The mannequin was without heating system in the body and positioned in the shower 0.8 m away from the showerhead; **(3)** The water was showered on the chest of the mannequin with an angle of approximately 30° | **(1)** DataRAM real-time particle monitor measured particles in the concentration range of 0.1 µg $m^{-3}$ to 400 mg $m^{-3}$ for particles less than 10 µm in diameter; **(2)** Aerodynamic Particle Sizer measured particle number and mass size distribution (in range of 1-30 µm) | $C_i = \frac{G}{\lambda}\left(1-e^{-\lambda t}\right)$ <br> $\lambda = \lambda_v + \lambda_w$ <br> $C_i$ — particle concentration; $G$ — particle generation rate, µg $m^{-3}$ $min^{-1}$; $\lambda_v$ — air exchange rate in the bathroom; $\lambda_w$ — the rate of particle losses due to deposition on the shower walls, floor, and body of mannequin in reciprocal minutes | 30.79-87.15 µg $m^{-3}$ $min^{-1}$ for cold water showering; 2252-2841 µg $m^{-3}$ $min^{-1}$ for hot water showering | Cold water (24-25 °C) showering and hot water (43-44 °C) showering |

**Table 2.3 Continued**

| Study | Experimental condition | Aerosol sampling equipment | Proposed aerosol balance equation | Aerosol generation rate | Remark of Water that supplied to tap/showerhead |
|---|---|---|---|---|---|
| O'Toole et al. (2009) | **(1)** Shower enclosure consisted of a 0.81 $m^2$ shower base with center drain; **(2)** Showerheads were installed at heights of 1900 mm (conventional showerhead) and 1880 mm (water efficient showerhead) and the showerhead was directed to spray on the back of the neck of a mannequin; **(3)** Air within the shower enclosure was saturated (i.e. relative humidity at, or close to, 100%) | **(1)** Aerodynamic Particle Sizer (APS): measuring particles in the size range from 500 nm to 5 µm; **(2)** Scanning Mobility Particle Sizer (SMPS): measuring particles in the size range from 15 nm to 700 nm; **(3)** Phase Doppler Particle Analyser (PDPA) measuring particles in the size range from 500 nm to 250 µm | – | – | Salt solutions were injected into source water; water temperature was kept constant, 38 or 42 $^{o}$C |

**Table 2.3 Continued**

| Study | Experimental condition | Aerosol sampling equipment | Proposed aerosol balance equation | Aerosol generation rate | Remark of Water that supplied to tap/showerhead |
|---|---|---|---|---|---|
| Bollin et al. (1985) | Air was collected above two shower doors and from the same rooms approximately 3 ft (91 cm) from the shower doors while the hot water was running | **(1)** An Andersen 1 AFCM viable (microbial) particle sizing sampler (Andersen Samplers, Inc., Atlanta, Ga); **(2)** An Andersen 1 AFCM two-stage viable particle sampler (Andersen Samplers, Inc.) | – | – | – |

### 2.4.1 Aerosol characteristics

Like any other airborne disease, the inflection of LD is affected by several factors, such as contaminated aerosol concentration, aerosol size distributions, breathing rate, exposure time and immunity (Carson 1996, Kowalski 2006), in which for definite ventilation style, the aerosol concentration in the space is related to appliance aerosol generation rate. It is believed that particles suspended in the air with size range from 3 to 100 μm are likely to be inhaled into the human respiratory system (ISI Incorporated 2013). O'Toole et al. (2009) indicated that aerosols of a size less than 10 μm in diameter were potentially associated with the inhalation exposure to microorganisms and biological agents which were with their potential deposition in the alveolar region of the lungs. Size distributions of aerosols generated by discharging showerheads have been investigated by several studies (Bollin et al. 1985, Xu and Weisel 2003, Zhou et al. 2007). Bollin et al. (1985) reported that approximately 90% (7 of 8 CFU) of recovered aerosolized droplets containing Legionella pneumophila during shower were between 1 and 5 μm in diameter. Xu and Weisel's (2003) study showed that the majority of the shower-generated aerosols were smaller than 0.3 μm, while these aerosols only contributed to approximately 2% of the measured total aerosol mass. Similar finding was reported by O'Toole et al. (2009), that more than 90% of total particle mass generated by showerheads was attributed to particles with diameter greater than 6 μm. Zhou et al.'s (2007) experimental study showed that the mass median diameter (MMD) of aerosol generated from showerheads running with hot water (43-44 $^{o}$C) was 5.2-7.5 μm, while the aerosol size was 2.5-3.1 μm when running with cold water (24-25 $^{o}$C). Moreover, as the aerosols are small in size, they could remain in the air for significant lengths of time because of the low settling velocity (Muhanned 2013).

Zhou et al. (2007) showed that aerosols from showerhead running with cold water had smallest mass median diameter with the largest geometric standard deviation compared with that from showerhead running with hot water. It was because that the room humidity during cold water showering was lower than that with hot water showering, making the evaporation of cold water droplet higher than that of hot water droplet (Zhou et al. 2007). It was revealed that in the environment with indoor relative humidity of 30%-70% and indoor temperature of 20 $^{o}$C, the evaporation time for an aerosol with an initial diameter of 20 μm decreasing to a half, 10 μm, was 0.17–0.4s (Nicas 2005). Keeping the air in test chambers or bathrooms saturated (i.e. relative humidity at 100%) or at one reference humidity level is helpful to eliminate or quantify the influence of humidity on the measured aerosol size. Humidity factor should be concerned in the future experimental studies of aerosol generation by showerheads. The impact of water temperature on tap/showerhead-generated aerosol size distribution was also analyzed by Carson (1996) from aspects of surface tension and viscosity, i.e. when water temperature raised from 20 $^{o}$C to 60 $^{o}$C, it would reduce surface tension by some 9% and halve the absolute viscosity. This indicates that keeping the shower water temperature unaltered during experimental study is necessary for accurately quantifying the aerosol generation, including aerosol generation rate and aerosol size.

The aerosol size distributions of conventional showerhead and water efficient ones were compared by O’Toole et al. (2009). Pair-wise analysis of particle concentrations (number of aerosols or droplet per cubic cm) in each size bins (0.2-1 µm, 1-2 µm, 2-3 µm, 3-6 µm, 6-10 μm, 10-20 μm) for water efficient showerheads and conventional ones did not show a consistent pattern that indicating a greater production of particles in the respirable particle diameter range (up to 6 μm) by either the conventional or water efficient showerheads (O'Toole et al. 2009). However, it was found that water efficient showerheads generated more small size aerosols (0.2-3 μm) compared with that of conventional ones.

As shown by above reviews, it can be seen that aerosol size distribution varies with showerhead type, shower water temperature, flow rate, density (salt solution or not) and surrounding air relative humidity. Nevertheless, aerosol generated by showerheads raise concerns as they are small enough to penetrate into the deep of lungs. As washroom is usually small, it can be assumed that the space is well mix/fill-up entirely with aerosols. Therefore, aerosol concentration in the bathroom is more important when considering the LD transmission, in which it is related to appliance aerosol generation rate. Among the several factors that influence the LD infection, this study focuses on the aerosol generation rate for showerheads only.

### 2.4.2 Factors affect aerosol generation rates

Currently available studies about impact factors of aerosol generation from showerheads were limited. Carson (1996) reported that aerosol generation rate was linked to the smoothness of the flow stream, i.e. at low flows, the streams from taps or showerheads tended to be broken and disorganized, which contributed to the aerosol generation; as the flow rate increased, the stream would become more continuous and smoother and the aerosol generation rate would decrease; increasing the flow rate further, then would increase the velocity of the stream and its turbulence, and resultantly increase the aerosol generation rate. Zhou et al. (2007) also revealed that aerosol generation rate increased with showerhead water flow rate. Temperature was identified by Zhou et al. (2007) and Carson (1996) that could affect the aerosol generation rates of showerhead. The impact of water temperature, flow rate and spray setting on aerosol formation was investigated by Cowen and Ollison (2006), and it revealed that although these parameters did have an effect on aerosol generation when within a single shower sampling run, no consistent effects for overall showerheads were found.

Even though several impact factors of aerosol generation for showerheads have been identified and investigated by these previous studies (Carson 1996, Cowen and Ollison 2006, Zhou et al. 2007), yet conclusive correlations are to be confirmed. Besides, the identified impact factors are limited; many potential impact factors, such as showerhead type, water pressure at showerhead, water velocity, spray spread angle, are not evaluated. Water jet momentum, which is correlated with water supply pressure, flow rate, velocity and orifice area, has been validated as the optimal parameter for the quantification of jet flow (Thomas et al. 1990). As shower spray is composed of plenty of water jets, the impact of water jet momentum on aerosol generation rate should be evaluated.

## 2.5 Summary

The penetration of water efficient appliances is increasing after several years' implementation of water efficiency labelling schemes, correspondingly the impact evaluation of the use of water efficient appliances becomes necessary. Mainly three aspects that corresponding to the three objectives defined in last chapter were reviewed here, namely household water consumption as well as associated energy use and corresponding $CO_2$ emissions, water supply system design and aerosol generation of water consuming appliances.

The reviews showed that the impact of water efficient appliances on water use was mainly evaluated on household level in existing studies. However, the household-level water consumption evaluation cannot reflect the water consumption diversity of individual person and specific water efficient appliance. Water consumption evaluation on individual level and for a specific appliance is suggested for the study in this thesis. Three factors including water use habit, rebound effect and consumer satisfaction were identified by the reviews that influenced the water consumption volume, which need to be considered for the studies about water consumption. The reviews also revealed that the quantification of associated energy use and corresponding $CO_2$ emissions with the water consumption should be localized and updated. Determining the $CO_2$ emission factor for water (kg-$CO_2$ $m^{-3}$) is one key step for the solution of water-related $CO_2$ emissions.

Large overestimation of design flow rate of water supply system was found by previous studies when using the methods provided in existing standards/guidelines. Comparatively, the predicted water demand by Monte Carlo method, e.g. Murakawa's simulation for water consumption (MSWC), was much closer to the field measured value. However, still overestimation of water consumption was identified when using existing models in MSWC. Deficiency in the definition of discharge overlapping among different types of appliances in the existing MSWC models is one key reason that causes the overestimation. Modified Monte Carlo model that handles the problem of discharge overlapping among different types of appliances properly is needed for the studies about determination of water demand as well as design flow rate. In this thesis, water demand by different types of appliances will be simulated separately first based on filed-surveyed water demand pattern, then the total water demand by all types of appliances will be acquired by summation of these separate simulation results. Instead of taking the maximum simultaneous water demand as the design flow rate like previous practices, for gravity tank water supply system, roof tank volume is suggested to be taken into account for the determination of design flow rate.

The reviews showed that chamber study was a proper method for investigation of aerosol generation by showerheads/taps, which will also be used for the aerosol generation study in this thesis. Glass material for the chamber is suggested in order to avoid the electrostatic effect in test chamber, which influences the measured aerosol concentration in the chamber. In previous studies, unclear definition of aerosol deposition was found while using aerosol balance equation for the calculation of aerosol generation rate, so that making the accuracy of the calculation compromised. Determining the aerosol deposition rate explicitly is the guarantee for the accurate estimation of aerosol generation rate. Computation fluid dynamics (CFD) simulation has been widely used for the study of indoor particulate contaminants, as a reference, it is proposed to be applied to the study of aerosol deposition in chamber.

# Chapter 3

# Methods of the study

## 3.1 Introduction

This chapter introduces different methods applied in this thesis for the achievement of the objectives defined in Chapter 1. First, details of showering questionnaire survey and field measurement in sample residential washrooms are described. The showering questionnaire survey and field measurement provides the input parameter values for the following Monte Carlo simulations. Then, Monte Carlo simulations of showering water consumption as well as associated energy use and corresponding $CO_2$ emissions are introduced, and models for the Monte Carlo simulations are proposed. After that, another Monte Carlo models for simulating the design flow rate of water supply system inside buildings are given. Experimental study and computational fluid dynamics (CFD) simulations of aerosol generation of showerhead in test chamber are introduced, and mathematical expressions for determining the aerosol generation rate of showerhead are developed. Regression analysis is introduced for the analysis of the collected data.

### 3.2 Showering questionnaire survey and measurement

As reviewed in Chapter 2, factors of water use habit, rebound effect and satisfaction influence the household water consumption. In order to accurately evaluate the impact of low flow showerheads bathing on showering water consumption, questionnaire survey about the showering in household is needed. A total of 37 volunteers (from 10 local families) were recruited to give feedback on showering attributes in their respective residential washrooms (i.e. 10 different washrooms). The 10 families were randomly sampled from different groups, in which 3 households are well-off couples and families enjoying a comfortable lifestyle (Group B); 3 households are stable and educated families of moderate (Group C); and 4 households are mid-to-low income families living in urban and suburban homes (Group F) (Experian Hong Kong Limited 2010). These three groups account for about 40% of Hong Kong households (Experian Hong Kong Limited 2010). The sampling of the families is with consideration of the relationship between income and water use which has been demonstrated by several studies (ARCWIS 2002, Loh and Coghlan 2003). Besides, the sample households were got for long time measurement.

Research purpose and basic knowledge about the survey were explained to participants before the survey. First, each participant was interviewed to response for their showering experience with the already installed showerheads at home (thereafter called ‘existing showerhead’). Sample interview questions are shown in the Appendix. A laboratory-made apparatus which composed of a pressure gauge, a temperature sensor and a timer (all are common types), as shown in Figure 3.1, was installed in existing showering facilities at the 10 families to measure the showerhead operating time and shower water temperature.

Showerhead operating time and shower water temperatures were recorded for all participants with existing showerheads over a week. The measurement time period (i.e. one week) was considered appropriate as interviewees were found adapted with the existing showerhead settings, and they reported that showerhead operating parameters were remaining unchanged for months. After that period of time, the existing showerheads under investigation were replaced by identical low flow showerhead, i.e. Water Efficiency Labelling Scheme (WELS) rated Grade 2 showerheads (registration no. SB 10-0085; brand: DELONG; model: 100090335, single function), that were with a nominal flow rate of 11.5 L $min^{-1}$. Showerhead operating time and water temperatures were measured again from October 2013 to February 2014. At the end of the measurement period, user feedback on the WELS rated showerhead was gathered through further interviews. One thing needs to be stated is that the purpose of the questionnaire and measurement is to investigate the showering differences between conventional showerheads and low flow ones, therefore there are no strict requirements about the Grades of WELS rated showerheads, namely all low flow showerheads can meet the sampling requirements. Considering the limitation of the installation conditions for WELS rated Grade 1 showerheads in some households, the WELS rated Grade 2 showerhead is sampled to represent the low flow showerhead in this study.

Based on the measurement method by the HKWSD (Hong Kong Water Supplies Department 2011a, Hong Kong Water Supplies Department 2011b), i.e. using the apparatus as shown in Figure 3.1, flow rates of all showerheads (existing showerheads at the 10 families and the sample WELS Grade 2 showerhead) were measured with a water pressure range of 50-350 kPa at the showerhead inlet. Water discharged in a sample operation of about 10s was collected in a container and the average water supply flow rate was determined from the volume discharged divided by discharge time. Measurements were conducted onsite (i.e. washrooms at the 10 families) to determine the actual operating conditions as chosen by households and then continued in a university laboratory to decide the showerhead pressure-flow characteristics.

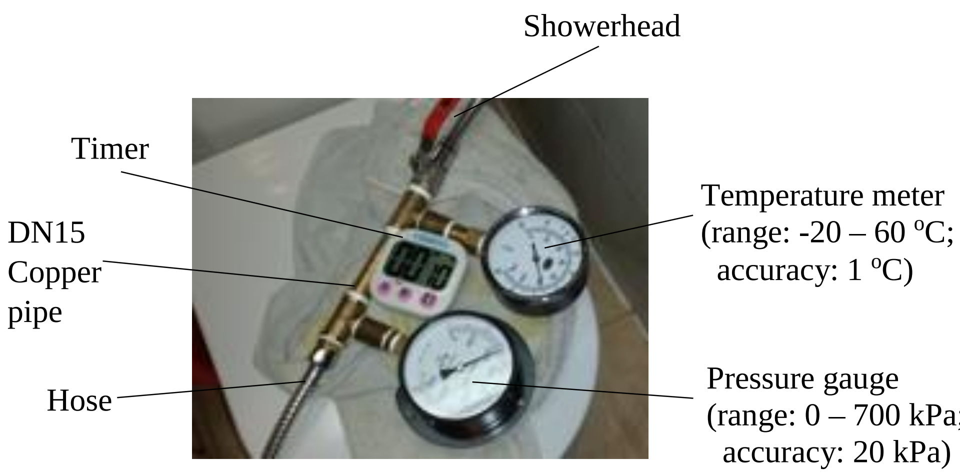



**Figure 3.1 Laboratory-made measurement apparatus**

## 3.3 Monte Carlo simulation of shower water consumption as well as associated energy use and corresponding $CO_2$ emissions

The reviews in Chapter 2 have showed that Monte Carlo simulation is a reliable method for the estimation of water consumption corresponding to the random characteristic of household water use. Based on the data collected from the survey as described in Section 3.2, Monte Carlo technique was applied to estimate the showering water consumption with conventional showerheads and low flow ones respectively, as well as associated energy use and corresponding $CO_2$ emissions. The Monte Carlo simulations are based on the development of Monte Carlo models (i.e. mathematical expressions).

### 3.3.1 Shower water consumption model

The model of per capita annual hot shower water consumption $V_p$ (m$^3$ ps$^{-1}$ yr$^{-1}$) is as following, where $v$ is showerhead flow rate (L min$^{-1}$), $i$ is a day in a year, $N_i$ is the expected number of showers per occupant per day, $t_s$ (s) is the expected showerhead operating time.

$$V_p = \frac{v}{60} \sum_i N_i \, t_s \tag{3.1}$$

The showerhead flow rate $v$, which is subject to user adjustments and limited by the maximum water supply flow rate, is described by, where $v_p$ is the maximum showerhead flow rate,

$$v = \begin{cases} v_p & ;v_p \le v^* \\ v^* & ;v_p > v^* \end{cases} \tag{3.2}$$

The user preferred showerhead flow rate $v^*$ (L min$^{-1}$) is given by a cumulative distribution function $\int_0^{v^*} f(v^*)dv$, which is shown in Figure 4.5 in following chapter. Users adjust showerhead flow rate based on their satisfaction. As reviewed in Section 2.2.3, the correlation of the satisfaction and influence parameter can be quantified by a logistic regression model. Taking the review as a reference, the user preferred showerhead flow rate $v^*$ (L min$^{-1}$) is expressed by a probabilistic user satisfaction φ as given in Equation 3.3, where $C_0$ and $C_1$ are proportional constants of the regression equation.

$$\varphi = \frac{\exp(C_0 + C_1 v^*)}{1 + \exp(C_0 + C_1 v^*)} \tag{3.3}$$

Local loss at showerhead is usually computed from the Equation 3.4, where *P* is the water supply pressure, ξ is the loss coefficient, *v* is the showerhead flow rate, *g* is the gravitational acceleration (Larock et al. 2000).

$$P = \xi \frac{v^2}{2g} \tag{3.4}$$

Defining showerhead resistance factor $k$ = ξ/2g, Equation 3.4 is rewritten as,

$$P = kv^2 \tag{3.5}$$

Therefore, the maximum showerhead flow rate $v_p$ (L min$^{-1}$) available from the water supply system can be determined by the showerhead water pressure $P$ (kPa) and the showerhead resistance factor $k$ (kPa min$^2$ L$^{-2}$),

$$v_p = \sqrt{\frac{P}{k}} \tag{3.6}$$

The showerhead water pressure $P$ (kPa) is given by the difference between the design static pressure at the showerhead $P_s$ (kPa) (in range of 150-350 kPa for typical high-rise water supply systems) and the pressure drop along the water supply pipe $P_L$ (kPa).

$$P = P_s - P_L \tag{3.7}$$

The pressure drop along the water supply pipe $P_L$ (kPa) is given by d'Arcy-Weisbach formula (Wise and Swaffield 2002) as following, where $\lambda$ is d'Arcy friction coefficient, $L_e$ is pipe length, $d$ is pipe diameter, $\rho_d$ is water density,

$$P_L = \lambda \frac{L_e}{d} \frac{\rho_d v^2}{2} \tag{3.8}$$

The change of pressure drop in the supply pipes from $P_{L,0}$ to $P_{L,1}$ corresponding to a flow rate from $v_0$ to $v_1$ in the water supply pipe due to the number of showerheads connected can be approximated by Equation 3.9, where the pipe friction loss range is $P_L/L_e$=0.1-0.5 kPa m$^{-1}$ with an equivalent pipe length range $L_e$=100-300 m (The Institution of Plumbing 2002, Wong 2002).

$$\frac{P_{L,1}}{P_{L,0}} \sim \left(\frac{v_1}{v_0}\right)^2 \tag{3.9}$$

### 3.3.2 Energy use model

Energy use as the hot water showering is divided into two parts to investigate: one part is the energy use for heating hot shower water at end use; the other part is the energy use in water supply process. Energy use for waste water disposal and recycle is not considered in this study.

Energy consumption for heating hot shower water at end use $E_{p,end}$ (GJ $ps^{-1}$ $yr^{-1}$) is given by Equation 3.10, where $\phi$=1 for a hot shower or 0 for a cold shower, $\rho_d$ (=1000kg $m^{-3}$) is the density of water, $c_p$ (=$4.2\times10^{-6}$ GJ $kg^{-1}$ $K^{-1}$) is the specific heat capacity of water, $V_{p,i}$ ($m^3$ $ps^{-1}$ $yr^{-1}$) is per capita per day shower water consumption, $T_{hot}$ (°C) is the expected hot shower water temperature, $T_{cold}$ (°C) is the cold water temperature.

$$E_{p,end} = \phi \rho_d c_p \sum_i V_{p,i} \left(T_{hot} - T_{cold}\right) \tag{3.10}$$

Wong et al.'s (2010) survey study showed that water supply temperature, namely cold water temperature $T_{cold}$ (°C), was significantly correlated with outdoor air temperature $T_a$ (°C) (Correlation coefficient R=0.97, p≤0.01, t-test). $T_{cold}$ (°C) expressed by $T_a$ (°C) is as Equation 3.11 (Wong et al. 2010), and the expression is used in this study.

$$T_{cold} = 10.4T_a^{0.29} \tag{3.11}$$

The outdoor air temperature variation recorded in Hong Kong in years 1884-2006 was purchased from the Hong Kong Observatory, as shown in Figure 3.2.

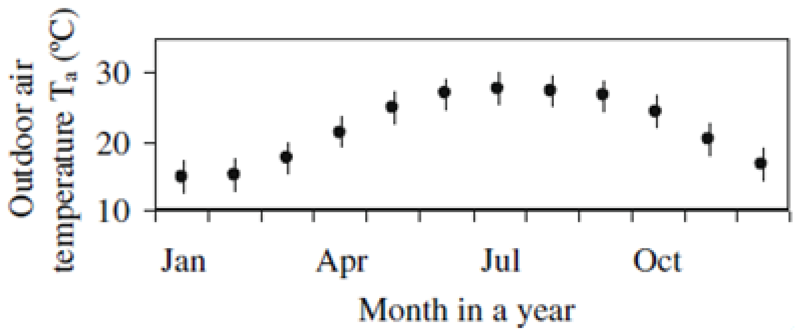



**Figure 3.2 Monthly profile of outdoor air temperature (Wong et al. 2010)**

Energy consumption in water supply process $E_{p,process}$ (kWh ps$^{-1}$ yr$^{-1}$) is given by Equation 3.12, where ψ (kWh m$^{-3}$) is energy consumption intensity of water.

$$E_{p,process} = \psi V_p \tag{3.12}$$

In this study, the energy consumption intensity of water ψ is calculated by the sum of energy consumption per unit water at the stages of water treatment, municipal supply and pumping inside buildings. Energy consumption per unit water for water treatment and municipal supply was 0.581 kWh m$^{-3}$ based on the Hong Kong Water Supplies Department 2014/15 Annual Report (Hong Kong Water Supplies Department 2015). Besides, a previous study in Hong Kong showed that pumping 76 m$^3$ water in tall buildings consumed 48 kWh electricity (Wong et al. 2017), correspondingly the energy consumption per unit water was 0.63 kWh $m^{-3}$. Therefore, the energy consumption intensity of water $\psi$ was 0.581 +0.63=1.211 kWh $m^{-3}$. The constant $\psi$ value (=1.211 kWh $m^{-3}$) is used in this study.

### 3.3.3 $CO_2$ emission model

Carbon dioxide emissions from hot showers are related to the energy consumption in the water supply process and at the end use for heating hot water. Per capita annual $CO_2$ emissions $m_p$ (kg-$CO_2$ $ps^{-1}$ $yr^{-1}$) from hot showers is given by Equation 3.13, where $\beta$ (kg-$CO_2$ $GJ^{-1}$) are the $CO_2$ emission factor for energy.

$$m_p = \beta\left(E_{p,process} + E_{p,end}\right) \tag{3.13}$$

Considering Equation 3.12, Equation 3.13 is rewritten as,

$$m_p = \beta\psi V_p + \beta E_{p,end} \tag{3.14}$$

Define $CO_2$ emission factor for water $\alpha$ (kg-$CO_2$ $m^{-3}$) = $\beta\psi$, Equation 3.14 is expressed by,

$$m_p = \alpha V_p + \beta E_{p,end} \tag{3.15}$$

In this study, the $CO_2$ emission factor for energy $\beta$ is for electricity specifically, and $\beta$=0.78 kg-$CO_2$ kWh$^{-1}$ (0.20 kg-$CO_2$ MJ$^{-1}$) was used according to the HK (Hong Kong) Electric Investments Sustainability Report (2015). Therefore, $CO_2$ emission factor for water $\alpha=\beta\psi$=0.78 kg-$CO_2$ kWh$^{-1}$×1.211 kWh m$^{-3}$ = 0.94 kg-$CO_2$ m$^{-3}$.

### 3.3.4 Monte Carlo simulation procedures

Monte Carlo simulations were used in this study to obtain the confidence intervals for water and energy consumption and to determine the $CO_2$ emissions associated with the consumption. The simulation process was as follow. A uniformly distributed random number $x\in[0,1]$ was taken from a random number set generated by the prime modulus multiplicative linear congruential generator (Park and Miller 1988). It was noted that this random number set was tested and applied in a number of engineering applications (Wong and Mui 2005, Mui et al. 2008, Wong and Mui 2008, Wong and Mui 2009). The input parameters for Equations 3.1 - 3.15 (i.e. $\zeta_i=\{N_i, \phi, t_s, T_{hot}, T_a, k, P_s, P_L, L_e\}$) were sampled from descriptive parametric distribution functions (Zwillinger and Kokoska 1999). The input value $\zeta_{i,x}$ of each parameter $\zeta_i$ was then determined from the descriptive distribution function $\tilde{\zeta}_i$ at percentile $x$ (Ross 2002), in which the descriptive distribution functions for parameters $N_i$, $\phi$ were given by reviews as described in Table 2.5; the descriptive distribution functions for parameters $P_s$, $P_L$, $L_e$ were given above in Section 3.3.1; the descriptive distribution functions for parameters $t_s$, $T_{hot}$, $k$ would be given by the survey study as described in Section 3.2. The input parameter values are summarized in Table 3.1, in which the highlighted parts are the results got by this study that will be described in following Section 4.3. The procedure was coded with Fortran and executive on desktop computer (Chivers and Sleightholme 2000).

$$\zeta_i = \zeta_{i,x} \ ;$$

$$\int_0^{\zeta_{i,x}} \tilde{\zeta}_i d\zeta_i = x \ ;$$

$$\zeta_i \in \tilde{\zeta}_i \tag{3.16}$$

**Table 3.1 Input parameters**

| Parameter | Values | Distribution | Reference | Remark |
|---|---|---|---|---|
| Water-$CO_2$ emission factor, $\alpha$ (kg-$CO_2$ $m^3$) | 0.94 | Constant | HK Water Supplies Department (2015), Wong et al. (2017) | |
| Energy-$CO_2$ emission factor, $\beta$ (kg-$CO_2$ $MJ^{-1}$) | 0.20 | Constant | HK Electric Investment Sustainability Report 2015 | |
| Number of showers per resident per day, $N_i$ ($hd^{-1}d^{-1}$) | range=1-3, mean=1.6 (Jun-Aug) | Discrete | Wong et al. (2010) | |
| | range=1-3, mean=1.1 (Sep-May) | Discrete | Wong et al. (2010) | |
| | mean=1.04 (Sep-Jan) | Discrete | Hong Kong Water Supplies Department (2011b) | For model validation |
| **Showerhead operating time $t_s$ (s)** | **mean=316–13*k*, CI=185-1093** | **Log-normal** | | **Section 4.2** |
| | mean=402, CI=178-910 | Log-normal | Hong Kong Water Supplies Department (2011b) | For model validation |
| Hot showers, $\phi$ | 97% (Jun-Aug) | Discrete | Wong et al. (2010) | |
| | 100% (Sep-May) | Discrete | Wong et al. (2010) | |
| **Shower water temperature, $T_{hot}$ (ºC)** | **mean=36.2 + 1.1*k*, range=33.4-42.7, sd=2.6** | **Normal** | | **Section 4.2** |
| Ambient temperature, $T_a$ (ºC) | Hong Kong weather data in the years of 1884 -1939, 1947-2006 | Normal | Wong et al. (2010) | |
| Showerhead resistance factor, $k$ (kPa $min^2$ $L^{-2}$) | mean=3.8, sd=1.74 | Discrete | Hong Kong Water Supplies Department (2011b) | For model validation |
| | 0.81-9.04 | Uniform | Cheung et al. (2015) | |
| Static water pressure at showerhead, $P_s$ (kPa) | range=150-350 | Uniform | Institute of Plumbing (2002) | |
| Pipe friction loss, $P_L$ (kPa $m^{-1}$) | range=0.1-0.5 | Uniform | Institute of Plumbing (2002) | |
| Supply pipe length, $L_e$ (m) | range=100-300 | Uniform | Wong (2002) | |

Notes: SD=standard deviation; CI=99% confidence interval

## 3.4 Monte Carlo simulation of design flow rate for water supply system inside buildings

Monte Carlo simulations of design flow rate for a case high-rise roof tank water supply system that feeds appliances including showerheads, wash basins, kitchen sinks and washing machines were performed. One previous investigation shows that many newly constructed government-founded residential buildings in Hong Kong are over 40 storeys or over 100 m (Cheng et al. 2008). Based on the current situation of residential building height in Hong Kong, the installation number of 600 for each type of appliances in the case high-rise roof tank water supply system was assumed. The Monte Carlo simulations were carried out in two steps: the first step is to simulate the simultaneous water demand by all types of appliances along the time series; the second step is to integrate the water demand time series to determine the design flow rate, in which roof tank volume was considered in the integration process to include its influence on the design flow rate. In the first step of Monte Carlo simulations, water demand time series of each type of appliance was simulated first, then the water demand of each type of appliance was summed up along the time series to obtain the total water demand time series. Moreover, two cases were considered: Case A is that all appliances fed by the water supply system were conventional ones; Case B is that 600 showerheads were low flow ones, while other types of appliances, including wash basins, kitchen sinks and washing machines, were conventional ones. Correspondingly, the integrations in the second step of Monte Carlo simulation were for these two water demand cases. Monte Carlo models of design flow rate for water supply system are described below.

### 3.4.1 Models of design flow rate

For roof tank water supply systems inside buildings, 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 $\tau_\infty$ which start at $t_0$ and end at time $t_\infty$, where $V_\infty$ (L) is the total volumetric water consumption, $V_o$ (L) is roof tank storage volume (Mui and Wong 2012),

$$V_\infty = \int_{\tau_\infty} q_w \, dt \le q_o \tau_\infty + V_o;$$

$$\tau_\infty = t_\infty - t_0 \tag{3.17}$$

There are solution pairs ($V_o$, $q_o$) to Equation 3.17 at any time period within the time period of demand, $\tau_o \in \tau_\infty$, as graphed in Figure 3.3.

$$V_o = \max\left\{\int_{\tau_o} (q_o - q_w) dt\right\} \tag{3.18}$$

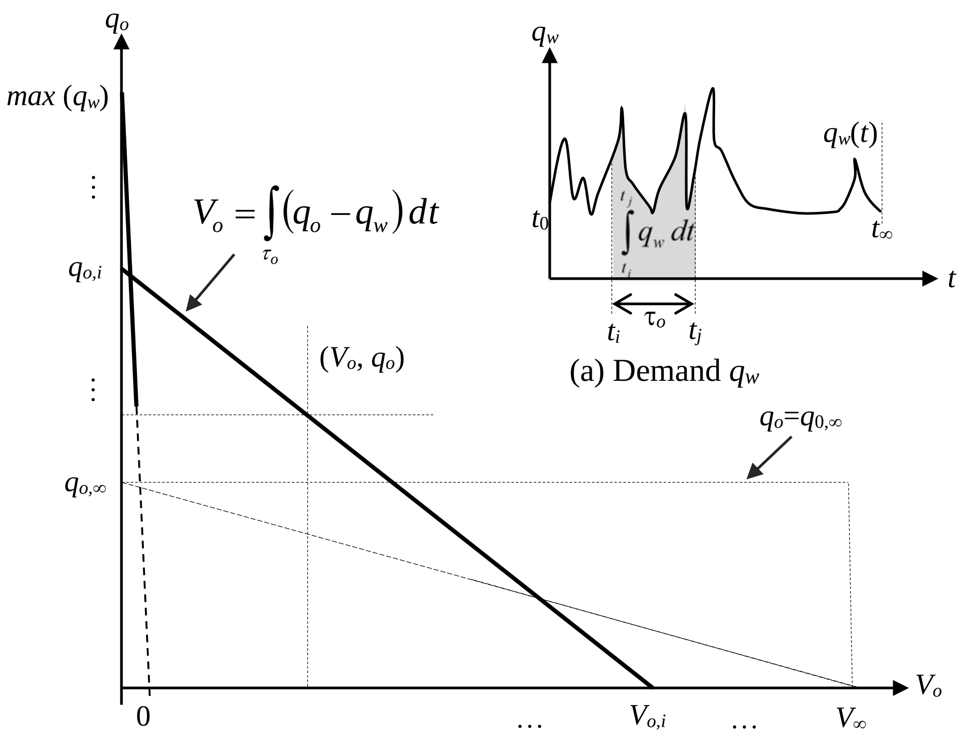
The required inflow rates for the minimum storage tank volume ($V_o = 0$) and the maximum storage tank volume ($V_o = V_\infty$) are $q_o = \max(q_w)$ and $q_o = q_{o,\infty}$ respectively,

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

$$q_{o,\infty} = \frac{V_\infty}{\tau_\infty} \tag{3.19}$$

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

$$q_w = \sum_k q_{c,k}(t) \tag{3.20}$$




(b) Solution pairs of storage volume $V_o$ and inflow rate $q_o$

**Figure 3.3 Mass balance at a water storage tank**

Operation of an appliance is random within a time period $\tau_w$ (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) (Mui and Wong 2013), and as shown in Figure 3.4.

$$\tau_w = t_{w,\infty} - t_{w,0}$$
$$= \begin{cases} \tau_{0,1} + \tau_{w,1} + \tau_{0,2} + \tau_{w,2} + \cdots + \tau_{0,l} + \tau_{w,l} + \cdots + \tau_{0,N_a} + \tau_{w,N_a} + \tau_{0,N_a+1} & ; \; t_{w2,N_a} \le t_{w,\infty} \\ \tau_{w,0} + \tau_{0,1} + \tau_{w,1} + \tau_{0,2} + \tau_{w,2} + \cdots + \tau_{0,l} + \tau_{w,l} + \cdots + \tau_{0,N_a} + \tau_{w,N_a} - \tau_{0,N_a+1} & \phantom{;} \; t_{w2,N_a} > t_{w,\infty} \end{cases} \tag{3.21}$$

$$\tau_{0,l} = t_{w1,1} - t_{w2,l-1} ; \; \tau_{w,l} = t_{w2,l} - t_{w1,l} \tag{3.22}$$

$$\tau_{0,1} = \begin{cases} t_{w1,1} - t_{w,0} \\ t_{w1,1} - t_{w2,0} \end{cases} ; \; \tau_{0,N_a+1} = \begin{cases} t_{w,\infty} - t_{w2,N_a} & ; \; t_{w2,N_a} \le t_{w,\infty} \\ t_{w2,N_a} - t_{w,\infty} = t_{w2,0} - t_{w,0} = \tau_{w,0} & \phantom{;} \; t_{w2,N_a} > t_{w,\infty} \end{cases} \tag{3.23}$$

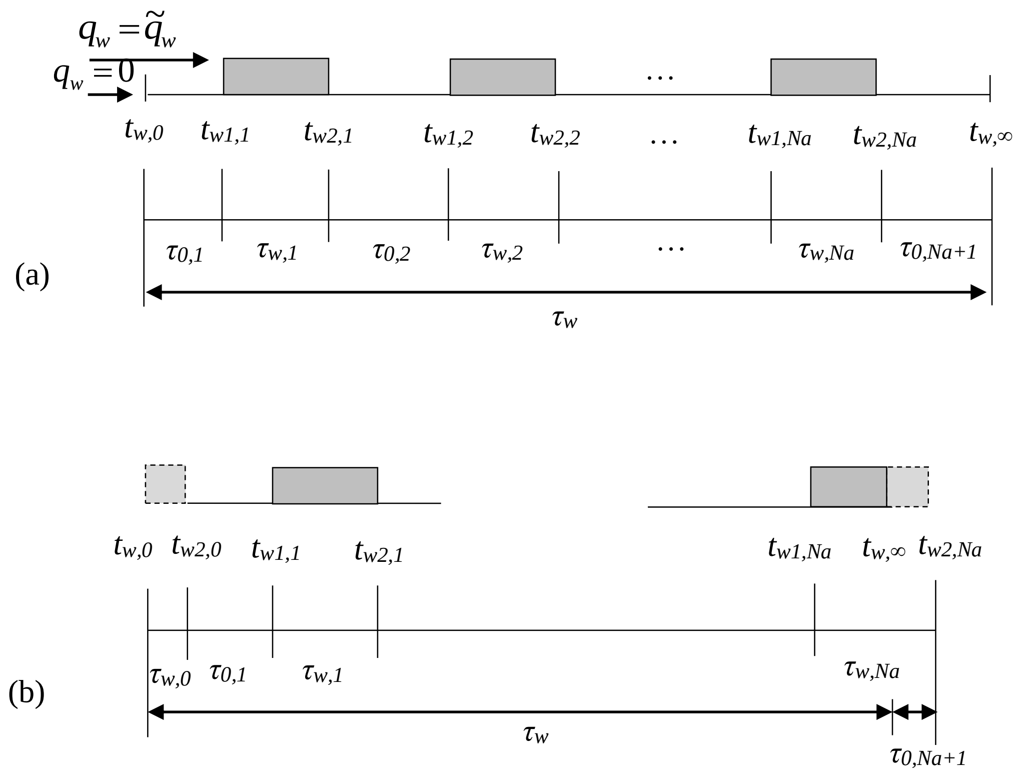



**Figure 3.4 Demand time series of an appliance (Mui and Wong 2013)**

The demand start time $t_{w1,l}$ (s) is given by a randomly distributed fractional demand start time $\hat{t}_{w1,l}$ (s), which can be determined via Monte Carlo simulations using a uniformly distributed fractional demand start time $U$ (s), where $\vartheta \in [0,1]$ is a random number between 0 and 1.

$$t_{w1,l} = \hat{t}_{w1,l} \tau_w;$$

$$\vartheta = \int_{-\infty}^{\hat{t}_{w1,l}} U \, dt \qquad (3.24)$$

Taking showering as an example, the non-zero demand period $\tau_{w,l}$ (s) can be obtained from distribution functions $\tau_{w,l} \in \tilde{\tau}_{w,l}$ via the Monte-Carlo sampling technique.

$$\vartheta = \int_{-\infty}^{\tau_{w,l}} \tilde{\tau}_{w,l} d\tau \tag{3.25}$$

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 $\gamma(t)$, 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 $m^{-2}$) (Wong and Mui 2007a). The values of $n_a$ for showering and $\gamma(t)$ in typical Hong Kong residential buildings were given by open literature, as reviewed in Section 2.3.4. Previous survey studies showed that the average number of occupant per household in Hong Kong is 4.2 (Wong and Mui 2004a, Wong and Mui 2004b, Wong and Mui 2007a), as reviewed in Section 2.3.4, so the $N_{p,max}$=4.2 persons was used in this study.

$$N_a(t) = n_a N_p(t) = n_a N_{p,\max}\gamma(t) = n_a O_a A_f \gamma(t) \tag{3.26}$$

### 3.4.2 Energy efficiency evaluation of the design flow rate

Simulated design flow rates with conventional showerhead demands and low flow showerhead demands were evaluated respectively from energy efficiency aspect, in order to justify the redesign of water supply system with low flow showerheads for bathing. The models for evaluation of energy efficiency are described below.

Design flow rate influences the friction loss in the up-feed pipe of roof tank water supply systems, further affects the system energy efficiency. Energy efficiency of a roof tank water supply system in high-rise buildings, which can be determined using the system heights (as shown in Figure 3.5), 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 $E_{pump}$ (Cheung et al. 2013),

$$\alpha_t = \frac{E_{out}}{E_{pump}} \tag{3.27}$$

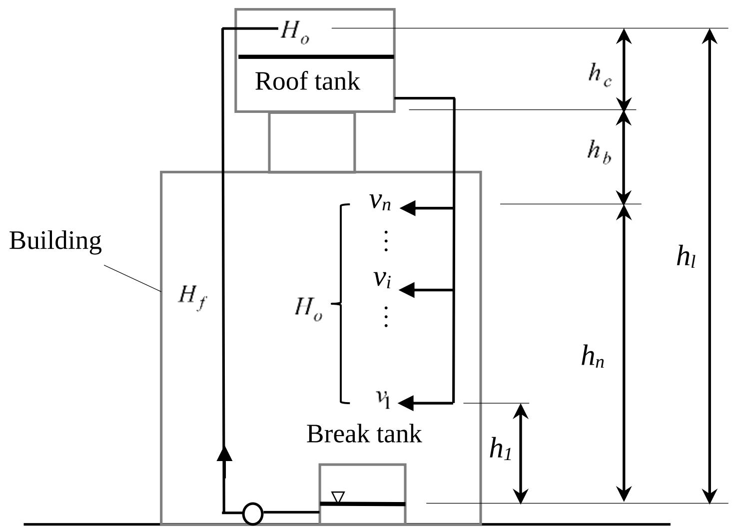



**Figure 3.5 A high-rise roof tank water supply system**

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

$$E_{out} = \rho_d g \sum_{i=1}^{n} v_i h_i \tag{3.28}$$

Pumping energy of lifting water from the break tank to the roof tank $E_{pump}$ (MJ) is defined in Equation 3.29, where $\eta_{ov}$ 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 3.30, where $\lambda$ is the d'Arcy friction coefficient, $u$ (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 (The Institute of Plumbing 2002).

$$E_{pump} = \frac{\rho_d g \sum_{i=1}^{n} v_i \left(h_l + H_f + H_o\right)}{\eta_{ov}} \; ; \; h_l = h_c + h_b + h_n \tag{3.29}$$

$$H_f = \lambda \frac{u^2}{2gd} L_e \tag{3.30}$$

It is noted that the design overall transmission efficiency $\eta_{ov}$ (34-65%) accounts for 50-80% of the pump efficiency $\eta_p$, about 90% of the mechanical transmission efficiency $\eta_{mt}$ and 70-90% of the electric motor efficiency $\eta_e$ (Kaya et al. 2008, Wong et al. 2014b).

$$\eta_{ov} = \eta_p \eta_{mt} \eta_e \tag{3.31}$$

In practice, an average height of demand locations $h_d$ can be used, correspondingly Equation 3.28 can be converted into Equation 3.32. Combined with Equation 3.29, energy efficiency $\alpha_t$ can be expressed by Equation 3.33.

$$E_{out} = \rho_d g h_d \sum_{i=1}^{n} v_i \tag{3.32}$$

$$\alpha_t = \frac{h_d \eta_{ov}}{h_l + H_f + H_o} \tag{3.33}$$

The pump power $P_t$ (kW) is given by,

$$P_t = \frac{q_o \left(H_f + H_o\right)}{100\,\eta_{ov}} \tag{3.34}$$

### 3.5 Experimental and computational study of showerhead aerosol generation rate

Experimental study of aerosol generation rate of sample showerheads was carried out in a mechanically ventilated chamber first. Then, computational fluid dynamics (CFD) simulations of aerosol generation in the chamber based on the experimental setup were performed. A mass balance equation for the aerosol concentration in the chamber was developed, which includes terms of aerosol mass generation rate, aerosol mass exhaust rate and aerosol mass deposition rate. In the aerosol mass balance equation, term of aerosol mass exhaust rate was determined by the experimental study, and term of aerosol mass deposition rate was determined by the CFD simulations. Based on the results acquired by the experimental study and CFD simulations, aerosol generation rates of sample showerheads were acquired by the proposed aerosol mass balance equation. Moreover, shower spray attributes of sample showerheads were measured by a laboratory-made apparatus. Correlations between aerosol generation rate and shower spray attributes were statistically analyzed. Details are described below.

### 3.5.1 Experimental study of aerosol generation by showerheads

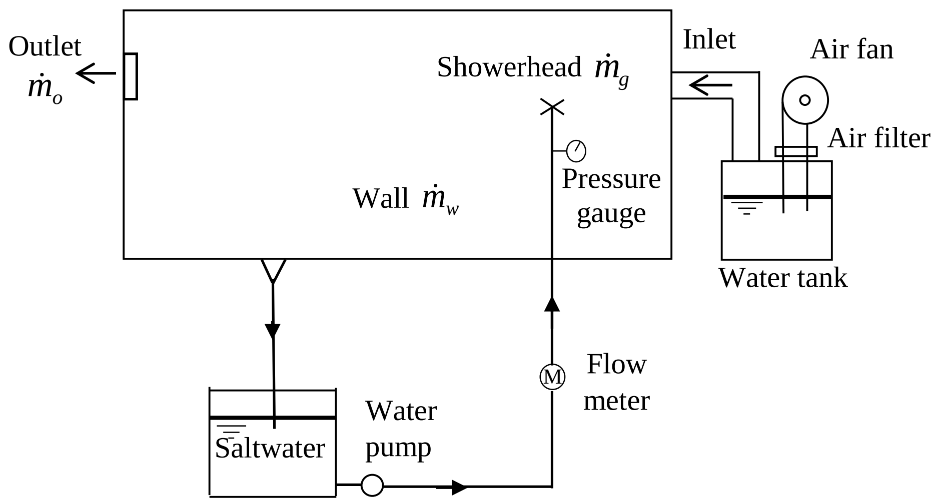
Figure 3.6 shows a showerhead installed in an experimental glass chamber of size 0.914 m × 0.61 m × 0.508 m. An air supply fan with air filter and a suction line at the inlet are also shown. The chamber was mechanically ventilated. Air was filtered and moistened before supplying through the chamber inlet, which was 0.155 m in diameter, at a steady air velocity of 0.25 $ms^{-1}$ (60 air changes per hour). The sample showerhead was fed from an enclosed tank filled with 2% saltwater solution (0.4 kg salt dissolved in 20 L distilled water) at pressure $P$ (kPa), in which the pressure $P$ is read from the pressure gauge installed in the water circulation system. The air fan, pressure gauge and flow meter installed in the experimental set-up are all common types.

Before the experiment, the mass of a dry and clean filter paper with a pore size of 0.2 μm was measured. Then the filter paper was placed at the chamber outlet to collect aerosolized saltwater for 3 hours (i.e. $\tau$ =10800 s). After the experiment, the filter paper sample was dried in an oven at 100ºC for 30 minutes (the baking time was determined according to no mass change of filter paper sample). The total collected salt mass $m_t$ (g) was determined by the filter mass difference before and after the experiment.

The aerosol mass exhaust rate $\dot{m}_o$ was determined by Equation 3.35, where $\rho_d$ (=1000 kg $m^{-3}$) and $\rho_t$ (=1020 kg $m^{-3}$) are the densities of water and saltwater respectively.

$$\dot{m}_o = \frac{(\phi_t + 1)m_t}{\phi_t \tau} \ ;$$

$$\phi_t = \frac{\rho_t - \rho_d}{\rho_d} \tag{3.35}$$




$\dot{m}_g$ - Aerosol mass generation rate

$\dot{m}_o$ - Aerosol mass exhaust rate

$\dot{m}_w$ - Aerosol mass deposition rate on walls

**Figure 3.6 Experimental set-up for showerhead aerosol generation study**

### 3.5.2 CFD simulations of aerosol generation by showerheads

The aerosol deposition fraction on chamber walls was calculated using CFD simulations. Figure 3.7 shows a geometric model chamber that was built based on the experimental set-up described above. As showerhead surface area is greatly less than the area of chamber walls, the aerosol deposition on showerhead surfaces is ignored in this study. Therefore, the showerhead can be represented by an aerosol generation source in the CFD simulation, and an absolute minimum size of the aerosol generation source is preferred in theory in order to avoid the deposition of aerosols on the surfaces of aerosol generation source. However, too much smaller size of aerosol generation source will cause the difficulty to convergence for the CFD simulation. In this study, a cubic zone with size of 0.01m×0.01m×0.01m was used to represent the discharging showerhead in the chamber. The model chamber was automatically 'medium' meshed using the Relevance Center setting in ANSYS Fluent 13.0, and the suitability of the mesh size was verified by comparing the simulated aerosol deposition fractions in different mesh size until there was no significant difference. Finally, 91007 calculation cells and 17449 nodes were set for the chamber.

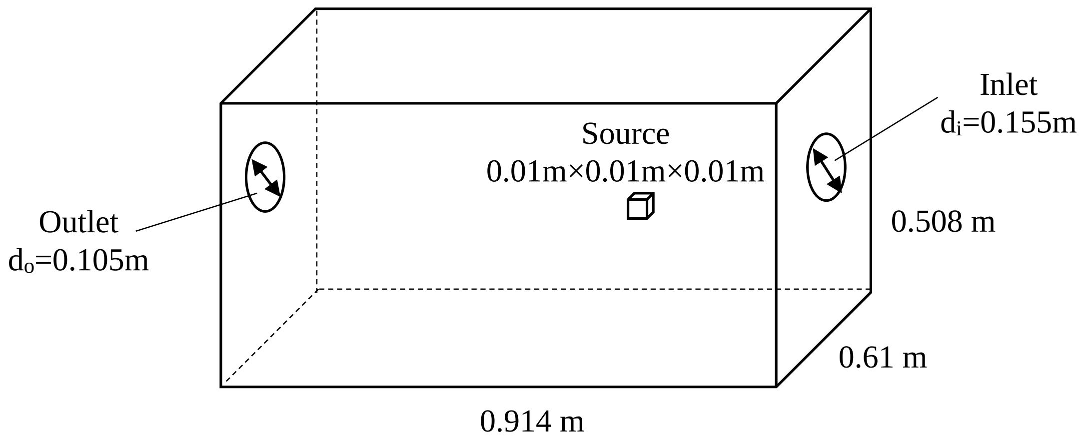



**Figure 3.7 Geometric model set-up for CFD simulations**

The Lagrangian discrete phase model (DPM) was employed to track the aerosols. The Lagrangian approach treats air phase as a continuous fluid by solving the Navier-Stokes equations, while tracks a large number of aerosols separately by solving equations of aerosol motion. As the mass and momentum loadings of the aerosol phase were low in the chamber, uncoupled DPM was adopted, meaning that the aerosol motion was influenced by the air phase motion, while the aerosol motion itself had no effect on the air phase motion. The number of stochastically tracked aerosols was verified by comparing with the ensemble average of the trajectories, namely simulated aerosol deposition fraction in this study. Finally, a statistical sample size of 12000 tracers was confirmed to represent the full range of aerosol behavior in this study.

The motion equation for aerosols is as following (ANSYS Fluent Theory Guide 2013), where $v_{pr}$ is aerosol velocity, $v_a$ is air phase velocity, $g$ is gravitational acceleration, $\rho_{pr}$ is aerosol density, $\rho_a$ is air density, $F_{ad}$ is additional force term (e.g. Brownian force, Saffman's lift force, thermophoretic force), $F_D(v_a-v_{pr})$ is the drag force per unit aerosol mass,

$$\frac{dv_{pr}}{dt} = F_D\left(v_a - v_{pr}\right) + \frac{g\left(\rho_{pr} - \rho_a\right)}{\rho_{pr}} + F_{ad} \tag{3.36}$$

$F_D$ was expressed below, where $\mu_a$ is molecular viscosity of the air, $d_{pr}$ is the aerosol diameter, $Re$ is the relative Reynolds number, $C_D$ is coefficient,

$$F_D = \frac{18\mu_a}{\rho_{pr} d_{pr}^{\;2}} . \frac{C_D R_e}{24} \tag{3.37}$$

The integration time scale $T_t$ of the aerosol motion equation is defined by Equation 3.38 (ANSYS Fluent Theory Guide 2013), where $v_{pr}'$ is the differential of aerosol velocity, $\tau$ is the time spent in turbulent motion along the aerosol path,

$$T_t = \int_0^{\infty} \frac{v_{pr}'(t) v_{pr}'(t-\tau)}{\overline{v_{pr}'^2}} d_\tau \tag{3.38}$$

A step Length Factor $\lambda_l$ (=1000) was used to control the integration time scale $T_t$ of the aerosol motion equation, expression is as Equation 3.39, where $\Delta t^*$ is the characteristic time that is related to the estimated time required for the aerosol to traverse the current continuous phase control volume,

$$T_t = \frac{\Delta t^*}{\lambda_l} \tag{3.39}$$

For the simulation with Lagrangian DPM, the aerosol injection from the source was just at the beginning of the computation of the continuous phase. A velocity inlet boundary condition was chosen for inlet, and outflow boundary condition were set at the outlet. The chamber wall was the 'stationary' boundary condition. The discrete phase boundary condition type of the inlet and outlet was set as 'escape', and 'trap' discrete phase boundary condition was chosen for the chamber wall. Source was set as 'reflect' discrete phase boundary condition, and the refection coefficients in the normal and tangent directions were 1. Standard *k-ε* Model was adopted since it is proper for airflow simulation in the space and good agreement between simulation results and measured data has been achieved (Stamou and Katsiris 2006).

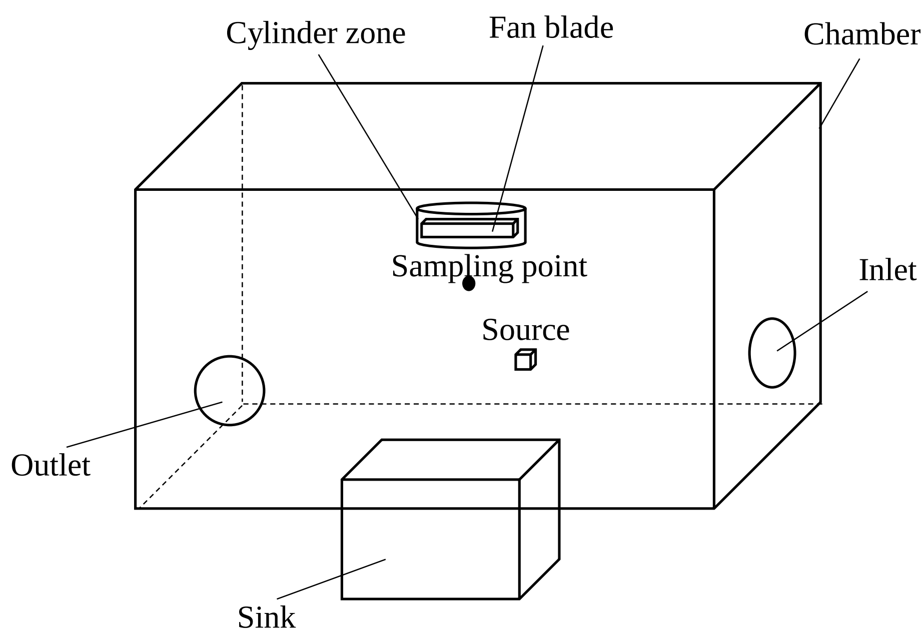
At steady state, total tracked aerosols (i.e. 12000 tracers) is the sum of the aerosols deposited on chamber walls and exhausted from outlet. The number of aerosol that deposited on chamber walls $n_w$ and exhausted from outlet $n_o$ were acquired from the CFD simulation, and aerosol deposition fraction $\phi_w$ is determined by following expression.

$$\phi_w = \frac{n_w}{n_w + n_o} \tag{3.40}$$

Contents below are another CFD simulation for the CFD model validation only.

For CFD model validation, another numerical simulation was performed with a chamber experimental setup by Carson (1996), and the simulation results were compared with Carson's (1996) experimental results. Figure 3.8 shows the geometric model setup used for the validation: test chamber size is 1.53m×0.84m×0.835m; sink size is

0.4m×0.33m×0.17m (the sink is located at the bottom of the chamber); circular air inlet and outlet are both 0.15 m in diameter; a flat rectangular blade (0.1m×0.02m×0.005 m) represents a mixing fan; a cylindrical zone of 0.12 m in diameter and 0.025 m in height is set for fan rotation in the simulations; and a cubic zone (0.01m×0.01m×0.01m) represents the aerosol generation source (i.e. discharging water appliance). Aerosol concentrations at the sampling point were determined from the simulation. It should be noted that the sampling point was the reference aerosol sampling location in the Carson's (1996) experiment.




Chamber (1.53m×0.84m×0.835m)
Sink (0.4m×0.33m×0.17m)
Inlet (diameter $d_i$ = 0.15m)
Outlet (diameter $d_o$=0.15m)
Fan blade (0.1m×0.02m×0.005m)
Cylinder zone (base diameter d = 0.12 m, height h = 0.025m)
Source (0.01m×0.01m×0.01m)

**Figure 3.8 Geometric model set-up for CFD simulations (for validation study)**

The model chamber was automatically ‘medium’ meshed using the Relevance Center setting in the ANSYS Fluent 13.0. The suitability of the mesh size was verified by comparing the simulated aerosol concentrations in the chamber under different mesh size until no significant change. Finally, 105846 calculation cells and 21361 nodes were set for the model chamber.

The Multiple Reference Frame (MRF) model in ANSYS Fluent 13.0 was adopted to model the flow involving the moving fan in the chamber. Renormalization Group (RNG) $k$-$\varepsilon$ model was selected to include the effect of swirl on turbulence, while standard wall functions were applied on the near-wall area.

The mixture model, one Euler-Euler multiphase model available in ANSYS Fluent 13.0, was employed to determine the airflow field and the aerosol concentration in the chamber numerically. In the mixture model, the air and aerosols are treated mathematically as interpenetrating continua. The volume fraction of aerosol phase is given by Equation 3.41 (ANSYS Fluent Theory Guide 2013), where $\delta_{pr}$ is the volume fraction of aerosol phase, $\rho_{pr}$ is aerosol density, $v_{ma}$ is mass-averaged velocity, $v_{dr,pr}$ is drift velocity of aerosol phase, $m_{a\text{-}pr}$ is the mass transfer from air phase to aerosol phase, $m_{pr\text{-}a}$ is the mass transfer from aerosol phase to air phase, $t$ is time and $n$ (=2) is number of phases,

$$\frac{\partial}{\partial t}\left(\delta_{pr}\rho_{pr}\right)+\nabla.\left(\delta_{pr}\rho_{pr}v_{ma}\right)=-\nabla.\left(\delta_{pr}\rho_{pr}v_{dr,pr}\right)+\sum_{q=1}^{n}\left(m_{a-pr}-m_{pr-a}\right) \tag{3.41}$$

Since the aerosols were fine in size, no slip velocity between air phase and aerosol particle phase was assumed in the mixture model. Partial equilibrium of pressure gradient and gravity were taken into account in the momentum equation for the air-aerosol mixture.

The aerosol was characterized as a salt water droplet with density of 1018 kg $m^{-3}$ and diameter of 4.94μm in the mixture model. Aerosols were injected into the chamber from the generation source continuously. A velocity inlet boundary condition was set at the inlet with initial air and aerosol velocities of 0.67 m $s^{-1}$ and 0 m $s^{-1}$ respectively. As there were no aerosols flowing into the chamber from the inlet, the aerosol volume fraction at the inlet was set as zero. An effective outflow boundary condition was chosen for the outlet, and the aerosol generation source was set as the mass flow inlet boundary condition. The mass flow rates of air and aerosols at the aerosol generation source were 0 kg $s^{-1}$ and $1.5\times10^{8}$ kg $s^{-1}$ respectively.

Four rotational speeds of the fan were set in the CFD simulations, i.e. 1000 revolutions per minute (rpm), 2000 rpm, 3000 rpm and 4000 rpm, and no heat transfer was considered in the numerical simulation. Table 3.2 outlines the parameters adopted in the simulations.

**Table 3.2 Parameters involved in the CFD simulations**

| Zone | Boundary condition | Parameter | Unit | Value | Remark |
|---|---|---|---|---|---|
| - | - | Ventilation rate $Q_v$ | $m^3\ s^{-1}$ | 0.0119 | Carson (1996) |
| - | - | Aerosol diameter $d_{pr}$ | m | $4.94\times10^{-6}$ | Carson (1996) |
| - | - | Aerosol density $\rho_{pr}$ | $kg\ m^{-3}$ | 1018 | Carson (1996) |
| - | - | Aerosol generation rate $\dot{n}_{pr}$ | Particles $s^{-1}$ | $2.34\times10^5$ | Carson (1996) |
| - | - | Rotational velocity of moving reference frame $\omega_r$ | rpm | 1000/2000/ 3000/4000 | - |
| Inlet | velocity inlet | Air velocity $v_{i,a}$ | $m\ s^{-1}$ | 0.67 | $v_{i,q}=Q/(\pi Ø_i^2/4)$ Mixture model |
| | | Aerosol velocity $v_{i,pr}$ | $m\ s^{-1}$ | 0 | Mixture model |
| | | Aerosol volume fraction $\delta_{pr}$ | - | 0 | Mixture model |
| Outlet | outflow | - | - | - | Mixture model |
| Source | mass flow inlet | Air mass flow rate $Q_{m,a}$ | $kg\ s^{-1}$ | 0 | Mixture model |
| | | Aerosol mass flow rate $Q_{m,pr}$ | $kg\ s^{-1}$ | $1.5\times10^{-8}$ | $Q_{m,pr}=(4/3)\pi(d_{pr}/2)^3\rho_{pr}n_{pr}$ Mixture model |
| Fan blade | moving wall | Relative rotational velocity $\omega_{relat}$ | rpm | 0 | Mixture model |
| Chamber, sink wall | stationary wall | - | - | - | Mixture model |

### 3.5.3 Aerosol mass balance model in the chamber

Inside a well-mixed ventilated chamber, the aerosol concentration of a generation source (discharging showerhead was an aerosol generation source in the chamber of this study) is given by the aerosol mass balance as expressed in Equation 3.42, where $\dot{m}_c$ (gs$^{-1}$) is the aerosol mass change rate, $\dot{m}_g$ (gs$^{-1}$) is the aerosol mass generation rate, $\dot{m}_i$ (gs$^{-1}$) is the aerosol mass inflow rate, $\dot{m}_o$ (gs$^{-1}$) is the aerosol mass exhaust rate, and $\dot{m}_w$ (gs$^{-1}$) is the wall deposition rate of the aerosol mass.

$$\dot{m}_c = \dot{m}_g + \dot{m}_i - \dot{m}_o - \dot{m}_w \tag{3.42}$$

Let the aerosol deposition fraction on the chamber walls be $\phi_w = \dot{m}_w / \dot{m}_g$ , the aerosol mass generation rate at steady state (i.e. $\dot{m}_c$ =0) and without any aerosols from inflow (i.e. $\dot{m}_i$ =0) is given by,

$$\dot{m}_g = \dot{m}_o + \dot{m}_w = \dot{m}_o / (1 - \phi_w) \tag{3.43}$$

The aerosol mass exhaust rate $\dot{m}_o$ (gs$^{-1}$) in Equation 3.43 can be determined in the experimental study described in Section 3.5.1, while the aerosol deposition fraction on the chamber walls $\phi_w$ can be calculated from the CFD simulations described in Section 3.5.2.

### 3.5.4 Experimental study of shower spray attributes

Shower spray attributes including water supply pressure at showerhead, water flow rate, spray spread angle and water distribution pattern within the spray cross-section, were measured by a laboratory-made water circulation system, as shown in Figure 3.9. A pressure gauge and a water meter were installed in the system, which are all common types. An annular gauge was placed 0.4m below the showerhead to measure the water distribution patterns within the spray cross-section. As shown in Figure 3.10, the annular gauge had four concentric circular arrays of graduated cylinders. A high speed camera (model: FPS1000; takes from 840 to over 10000 frames per second) was placed aside for taking photos of showerhead discharging.

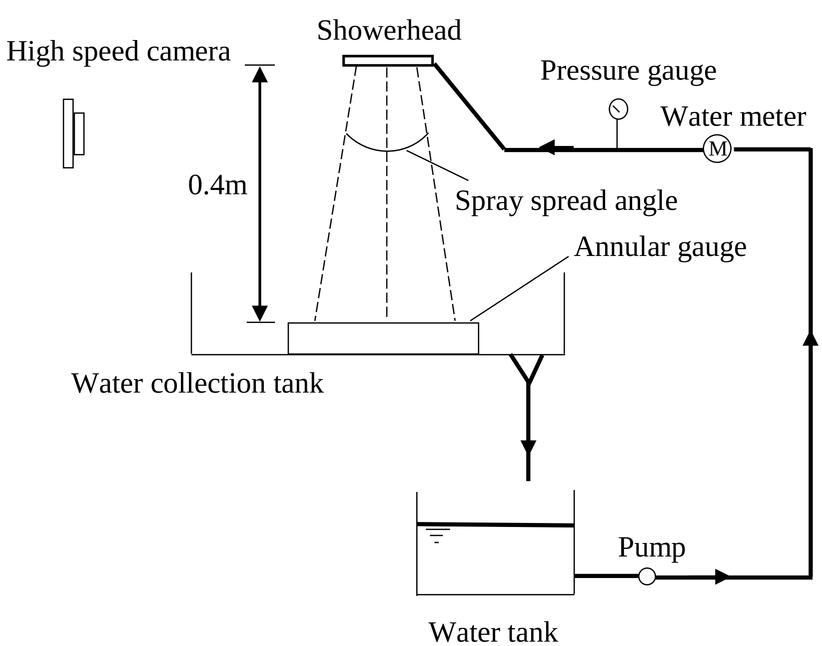



**Figure 3.9 Experimental set-up for measurement of shower spray attributes**

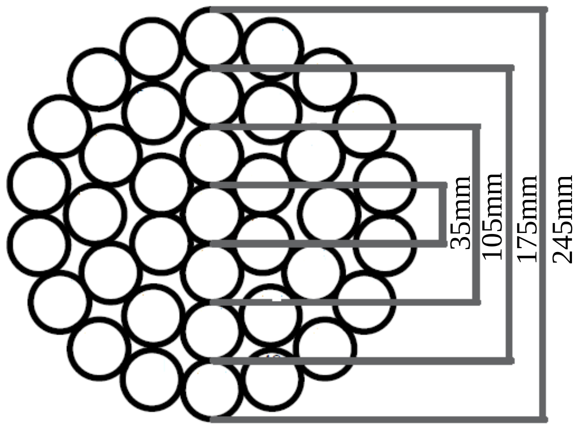



**Figure 3.10 Annular gauge**

The discharged water volume of a sample operation of about 20s was read from the water meter and the average water flow rate of a showerhead $Q_s$ was determined from the water volume divided by the operation time. Water flow rates under pressure range of 50-250 kPa were measured, in order to determine the showerhead resistance factor *k*.

The spray spread angle $\theta_s$ ($^o$) is obtained from a series of photos taken by the high speed camera (as shown in Figure 3.11) and then calculated by Equation 3.44, where $L_1$ (m), $L_2$ (m), $h_1$ (m), $h_2$ (m) are the lengths of the triangle bases and heights.

$$\tan\frac{\theta_s}{2} = \frac{\frac{L_1}{2}}{h_1 + h_2} = \frac{\frac{L_2}{2}}{h_2} \tag{3.44}$$

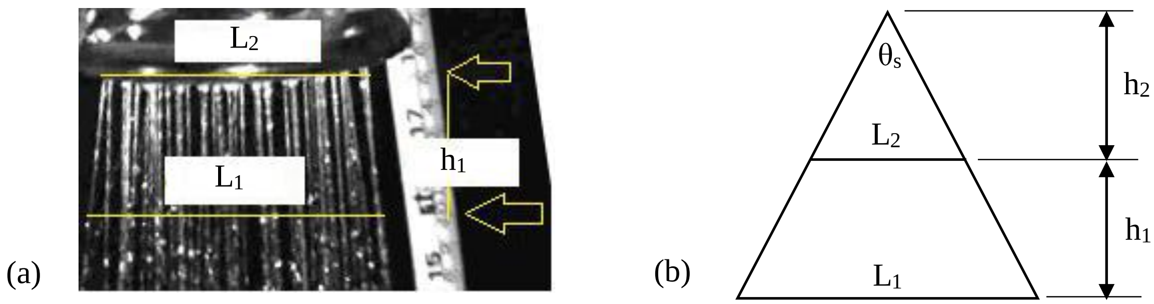



**Figure 3.11 Spray spread angle**

The spray jet momentum $M_s$ ($m^4\ s^{-2}$) is expressed by Equation 3.45 (Thomas et al. 1990), where $v_s$ ($ms^{-1}$) is spray jet velocity, which is determined from the showerhead flow rate $Q_s$ divided by the total nozzle area of a showerhead faceplate $A_s$ ($m^2$).

$$M_s = Q_s v_s \quad ;$$

$$v_s = \frac{Q_s}{A_s} \tag{3.45}$$

Water discharged in a sample operation of about 20s was collected by the annular gauge, and collected water volume in each circle of the annular gauge $V_{s,l}$ was measured. The percentage of water volume in each concentric circular array of the annular gauge $\chi_{s,l}$ is given by,

$$\chi_{s,l} = \frac{V_{s,l}}{\sum V_{s,l}} \tag{3.46}$$

Then, the water spray flow rate in each concentric circular array is calculated by Equation 3.47.

$$Q_{s,l} = Q_s \chi_{s,l} \tag{3.47}$$

The water spray uniformity $\phi_u$ is expressed by Equation 3.48, where $u_{s,l}$ (L s$^{-1}$ m$^{-2}$) is the mass flux density at a distance from the centerline of the showerhead $l_s$ (m), $A_{s,l}$ (m$^2$) is the water collection area of an annular gauge, as shown in Figure 3.12.

$$\phi_u = \frac{\bar{u}}{u_{\max}} \ ;$$

$$\bar{u} = \frac{\sum Q_{s,l}}{\sum A_{s,l}} \ ;$$

$$u_{s,l} = \frac{Q_{s,l}}{A_{s,l}} \ ;$$

$$u_{\max} = \max\{u_{s,l}\} \tag{3.48}$$

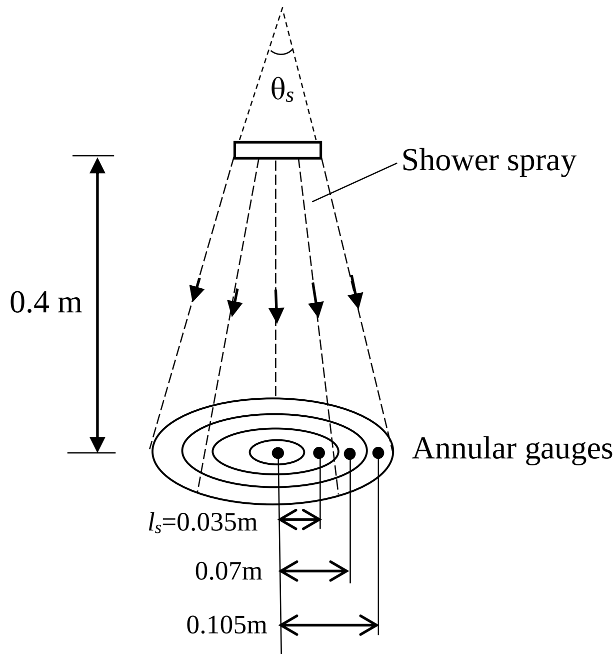



**Figure 3.12 Spray spread angle and water distribution patterns**

The annular gauges shown in Figure 3.12 can be replaced by an electronic scale to measure the spray jet force. The spray jet force $F_s$ (N) is calculated by Equation 3.49, where $m_r$ (kg) is the mass reading from the electronic scale when the showerhead is operating, $m_0$ (kg) is the mass of the water left on the electronic scale after showering and $g$ (m s$^{-2}$) is the gravitational acceleration.

$$F_s = (m_r - m_0)g \tag{3.49}$$

The spray jet force can also be expressed by spray attributes as given by Equation 3.50, where $\dot{m}_s$ is the water spray mass flow rate, $a_s$ is the spray jet acceleration, $\rho_t$ is the spray water density, $v_{s,h}$ is the spray jet velocity at a vertical distance of *h* below the showerhead, and $\tau$ is the time taken for the jet spray from the showerhead faceplate to reach *h*.

$$F_s = \dot{m}_s a_s;$$

$$\dot{m}_s = Q_s \rho_t;$$

$$a_s = \frac{v_{s,h} - v_s}{\tau} \tag{3.50}$$

### 3.5.5 Regression analysis

Regression analysis was used to analyze the correlations between aerosol generation rate and shower spray attributes. Regression equation is given by,

$$y \sim (x_1, x_2, x_3, \ldots, x_i, \ldots) \tag{3.51}$$

Considering that some independent variables in Equation 3.51 are interdependent, as expressed by,

$$x_1 \sim (x_{i+1}, x_{i+2}, \ldots);$$

$$x_2 \sim (x_{i+1}, x_{i+2}, \ldots);$$

$$x_3 \sim (x_{i+1}, x_{i+2}, \ldots) \tag{3.52}$$

The Equation 3.51 is rewritten with limited independent variables, as following,

$$y \sim (x_1, x_2, x_3, \ldots, x_i) \tag{3.53}$$

The correlations between dependent variable y and each independent variable $x_1$, $x_2$, $x_3$, …, $x_i$, are given first by,

$$y = \alpha_1 x_1^{\beta_1};\ y = \alpha_2 x_2^{\beta_2};\ y = \alpha_3 x_3^{\beta_3};\ \ldots;\ y = \alpha_i x_i^{\beta_i} \tag{3.54}$$

Then the correlation between dependent variable y and multi independent variables is expressed by,

$$y = \alpha x_1^{\beta_1} x_2^{\beta_2} x_3^{\beta_3} \ldots x_i^{\beta_i} \tag{3.55}$$

### 3.6 Summary

Different methods were described in this section in order to achieve the objectives defined in Chapter 1, including questionnaire survey and field measurement, Monte Carlo simulations, experimental study, computational fluid dynamics (CFD) simulations and regression analysis. Details of showering questionnaire and filed measurement in sample residential washrooms were introduced. The showering questionnaire and filed measurement provide the input parameter values for the following Monte Carlo simulations of shower water demand and design flow rate of water supply system. Models for the per capita annual shower water consumption and associated energy use and corresponding $CO_2$ emissions were proposed, and another models for simulating the design flow rate of water supply system inside buildings were developed. Details of experimental study of aerosol generation by showerheads and computational fluid dynamics (CFD) simulations of aerosol generation in chamber were discussed.

# Chapter 4

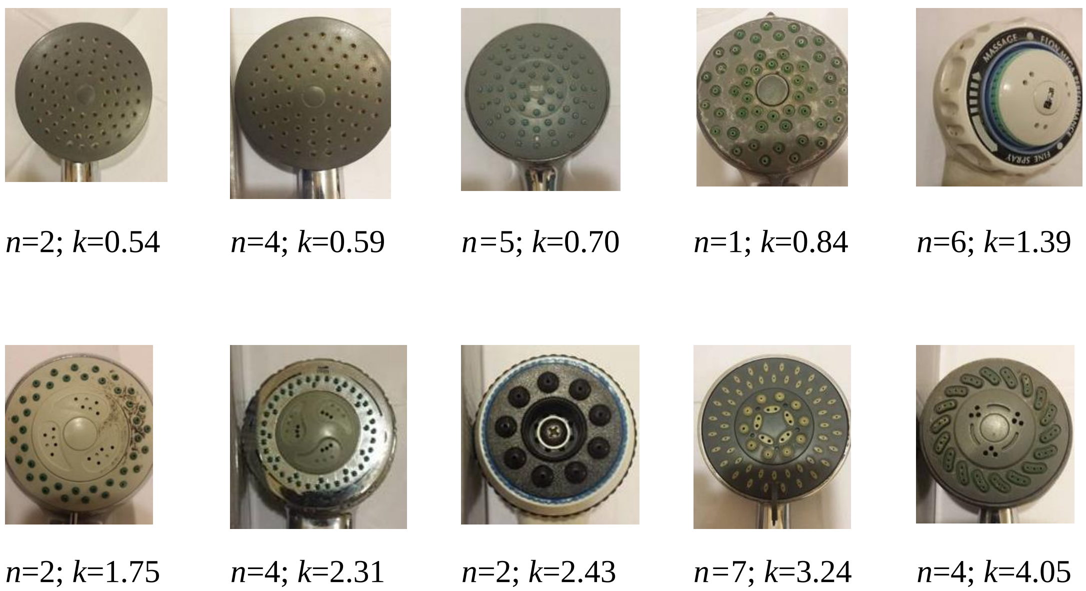
# Impact of low flow showerheads for bathing on shower water consumption as well as associated energy use and corresponding $CO_2$ emissions

## 4.1 Introduction

The results of the survey and measurement study described in Section 3.2 are presented and analyzed first in this Chapter. Parameters that influence the shower water consumption and the associated energy use are identified, and values or expressions of the parameters are given. Then shower water consumptions with the maximum showerhead flow rate and user preferred showerhead flow rate are evaluated respectively. Finally, the theoretically maximum benefits, i.e. showering water consumption, and associated energy use and corresponding $CO_2$ emissions, of low flow showerheads for bathing are quantified.

## 4.2 Survey results

Figure 4.1 shows the existing showerheads and the low flow showerhead, i.e. WELS rated Grade 2 showerhead, investigated at the 10 families, where *n* is the number of users, *k* is showerhead resistance factor (The *k* values are determined from the Figure 4.2 described in following). Showerhead designs and their hole configurations are illustrated. Some of these designs were flow rate adjustable to optimize user satisfaction. It was found that interviewees have adapted with the existing showerhead settings, and they reported that showerhead operating parameters were remaining unchanged for months.




**(a)**

*k*=2.46

**(b)**

**Figure 4.1 Showerheads under investigation: (a) showerheads already installed in 10 residential washrooms in Hong Kong; (b) a Water Efficiency Labelling Scheme (WELS) rated Grade 2 showerhead**

The survey study showed that all the existing showerheads installed in the 10 families were non-WELS rated. Although an earlier survey conducted by HKWSD (Hong Kong Water Supplies Department 2011b) indicated that 98.8% households supported water conservation measures and 36.4% of them were aware of WELS. This shows the difference between the consciousness of water conservation and actual water conservation behavior. Previous studies also have similar reports; it was revealed that positive environmental intention did not always translate to action of reducing water consumption (Kelly and Fong 2015, Graymore and Wallis 2010). More incentives are needed to promote the low flow showerheads in Hong Kong. This survey also reported that 32 participants preferred a fine mist spray while five preferred a powerful spray. Regarding showerhead performance, five participants (13.5%) were not satisfied with their existing showerheads but kept using them, in other words, it indicates that satisfaction of showerhead performance influenced the adoption of the showerhead.

Table 4.1 summarizes the showering attributes self-reported by interviewees. Thirty-four participants (92%) expressed that they were willing to have hot showers even in the summer period. This is consistent with a previous survey that found 97% of the summer showers were hot ones (Wong et al. 2010). The hot shower temperature ($T_{hot}$) preferred was between 37°C and 39°C, with an average of 38.6°C (SD=2.5°C). The average showerhead operating time ($t_s$) surveyed was 282s, with SD=108s. In the interviews, 28 participants (76%) reported that they would shampoo every day, eight (22%) every other day and one once every six days. The showerhead operating time for shampooing ranged from 2 to 6 minutes (average=2.9 minutes), and 24 participants (65%) usually took 2 minutes for shampooing. The expected daily showerhead operating time for shampooing was about 151s (i.e. average time weighted by the shampooing frequency). The total mean showerhead operating time was 433s (=282s+151s), and that was not significantly different from the HKWSD reference value (=402s) (Hong Kong Water Supplies Department 2011b). During the survey period, all participants took one shower daily (1 $d^{-1}$). This is again consistent with some previous survey results in Hong Kong: 1.04 times per day between mid-September and mid-January (Hong Kong Water Supplies Department 2011b) and 1.1 times per day (SD=0.3 times per day) from December to February (Wong et al. 2010).

**Table 4.1 Showering attributes self-reported by interviewees**

| Attribute | Unit | Expression | Other reference(s) |
|---|---|---|---|
| Hot water shower | - | 92% (summer months) | 97% (summer months)<br>(Wong et al. 2010) |
| $T_{hot}$ | °C | 38.6°C (SD=2.5°C) | 40.9°C (SD=1°C)<br>(Wong et al. 2010) |
| $t_s$ | s | 282s (SD=108s), shampoo excluded | - |
| $t_1$ | s | 180s (SD=85s), shampoo only | - |
| $t+t_1$ | s | 433s (SD=150s) | 402 s<br>(Hong Kong Water Supplies Department 2011b) |
| $N_j$ | - | 1 | 1.04<br>(Hong Kong Water Supplies Department 2011b)<br>1.1, SD=0.3 (winter months)<br>(Wong et al. 2010) |

### 4.3 Measurement results and discussions

#### 4.3.1 Showering attributes

Showerhead resistance factors *k* for the 10 surveyed showerheads are plotted in Figure 4.2. Based on the *k* values, the 10 surveyed showerheads are divided into 5 groups, in which Group 1 are showerheads with *k* values of 0.54-0.84 kPa $min^2$ $L^{-2}$, Group 2 are 1.39-1.75 kPa $min^2$ $L^{-2}$, Group 3 are 2.31-2.43 kPa $min^2$ $L^{-2}$, Group 4 is 3.24 kPa $min^2$ $L^{-2}$, and Group 5 is 4.05 kPa $min^2$ $L^{-2}$. The measured operating parameters of the 10 surveyed showerheads (the average outdoor temperature was 26.3°C during the measurement period, i.e. one week) are presented in Table 4.2. As shown in Table 4.2, the measured hot shower temperature $T_{hot}$, ranged from 36.8°C to 42.7°C, with an average of 38.5 °C (SD=2 °C), is not only comparable to the average hot shower temperatures reported in Japan (39°C) and Taiwan (36.1°C) but also consistent with a previous local measurement result (40.9°C) (Wong et al. 2010, Okamoto et al. 2015). The showerhead operating time $t_s$ ranged from 240s to 359s, with an average of 305 s (SD=107 s). Compared with the average hot shower temperature (38.6°C) and showerhead operating time (433 s) that self-reported by interviewees, the measured average hot shower temperature and showerhead operating time show no significant difference ($p \geq 0.4$, *t*-test). This indicates that users can accurately sense the shower water temperature and showering time to some extent by their subjective judgement. Further analysis, this might indirectly validate the water conservation potential by users' actively behavioral changes as water conservation education.

**Table 4.2 Showerhead operating parameters of the 10 surveyed showerheads (1-week)**

| Group | $n^*$ | $k$ (kPa min$^2$ L$^{-2}$) | $T_{cold}$ (°C) | $T_{hot}$ (°C) | $T_{hot}$–$T_{cold}$ (°C) | $v$ (L min$^{-1}$) | $t_s$ (s) | $V$ (L) |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 0.54-0.84 | 26.8 | 36.8 | 10.0 | 11.9 | 359 | 70.9 |
| 2 | 8 | 1.39-1.75 | 26.6 | 38.4 | 11.8 | 9.8 | 357 | 59.1 |
| 3 | 6 | 2.31-2.43 | 26.0 | 35.4 | 9.4 | 10.6 | 314 | 52.9 |
| 4 | 7 | 3.24 | 28.5 | 42.7 | 14.2 | 10.6 | 240 | 42.6 |
| 5 | 4 | 4.05 | 26.2 | 38.8 | 12.6 | 6.0 | 281 | 28.1 |

*Number of user

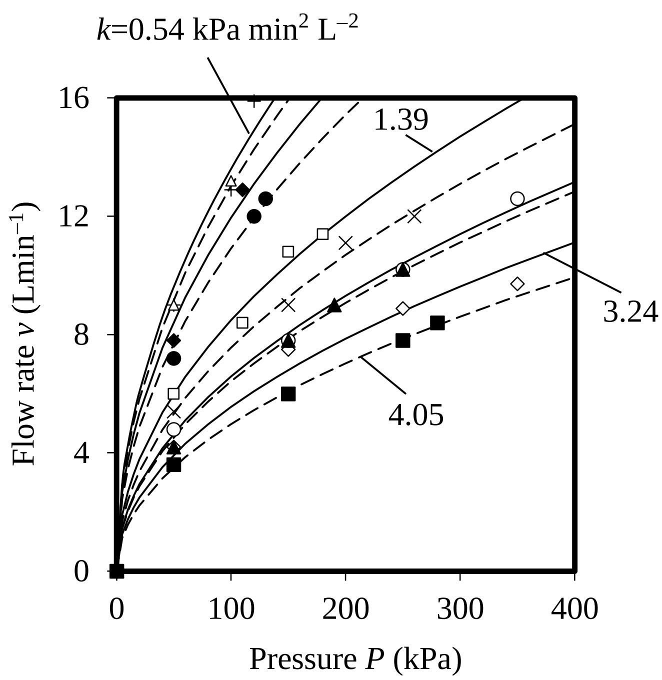



**Figure 4.2 Showerhead resistance factors *k* for the 10 surveyed showerheads**

Figure 4.3 graphs the predicted and measured cold water supply temperatures $T_{cold}$ at the surveyed showerheads as a confirmation to the Equation 3.11. A reference line indicating perfect prediction with measurement is shown in the figure. Good predictions were made as shown in the figure.

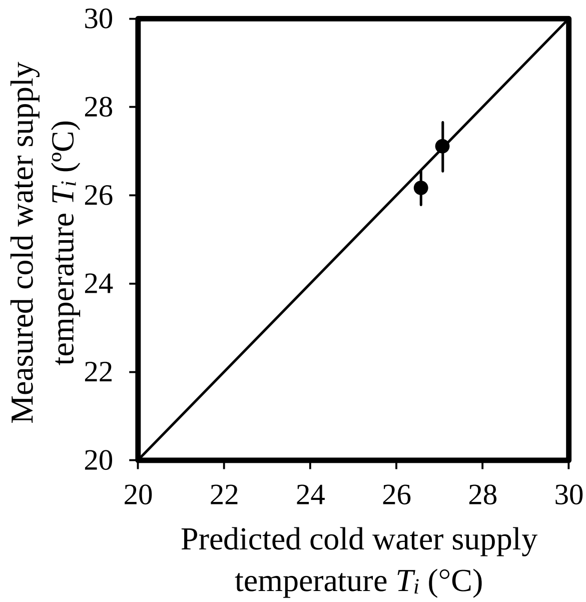



**Figure 4.3 Cold water supply temperatures at showerheads**

For the 10 surveyed showerheads, strong associations with showerhead resistance factor $k$ were reported for hot shower temperature $T_{hot}$ ($p<0.001$, $t$-test), temperature difference between hot and cold water supply $T_{hot}–T_{cold}$ ($p<0.0001$, $t$-test), flow rate $v$ ($p=0.05$, $t$-test) and water consumption $V$ ($p=0.05$, $t$-test), but not for showerhead operating time $t_s$ ($p=0.4$, $t$-test). Expressions of hot shower temperature $T_{hot}$, temperature difference between hot and cold water supply $T_{hot}–T_{cold}$, flow rate $v$, water consumption $V$ and showerhead operating time $t_s$ by showerhead resistance factor k were summarized in Table 4.3. A higher shower temperature was observed for showerheads with lower flow rates ($p=0.05$, $t$-test). This is consistent with an earlier laboratory study that showed lower flow showerheads resulted in increased shower temperatures for maintaining user comfort (Nishina and Murakawa 1997).

Measured four operating parameters, namely hot shower temperature $T_{hot}$, flow rate $v$, showerhead operating time $t$ and water consumption $V$, with operation of the sample WELS rated Grade 2 showerhead ($k=2.46$) (Figure 4.1b) for 5 months are exhibited in Table 4.4.

No significant difference of shower duration was reported between existing showerheads and low flow one ($p=0.4$, $t$-test). It demonstrated that shower duration was independent of the showerhead design. An earlier study reported a similar outcome (Toyosada et al. 2013). On the other hand, water consumption was apparently reduced in the first month after higher flow showerheads ($k<2.46$) had been replaced by a lower flow one ($k=2.46$); therefore, the use of low flow showerheads can improve water efficiency (Hong Kong Water Supplies Department 2011a).

It was found that outdoor temperature $T_a$ dropped significantly from the first 2 months (21.7-23.7°C) to the last 3 months (15.8-16.3°C) ($p<0.0001$, $t$-test). No significant difference between these 2 periods was found for shower temperature $T_{hot}$ ($p>0.05$, $t$-test), flow rate $v$ ($p>0.05$, $t$-test) and water consumption $V$ ($p>0.05$, $t$-test). However, significantly longer shower durations were reported for Groups 1, 3 and 5 ($p\leq0.05$, $t$-test).

The shower duration increased from 297s to 327s (i.e. for an outdoor temperature drop of 6°C, the shower duration was 10% longer) in the two periods. A plot of showerhead operating time $t_s$ against outdoor temperature $T_a$ suggested a strong association (correlation coefficient R=0.7, $p$=0.001, $t$-test). Shower operating time is one of the dominating factors of heating energy use for hot water and it may be related to a number of factors such as human thermal comfort and behavior response to climate. Hence, the expected showerhead operating time against the outdoor temperature can be expressed as follows with a standard deviation $\sigma_t$,

$$t_s = 397 - 4.4\, T_a\ ;$$

$$\sigma_t = 0.08\, t_s \tag{4.1}$$

**Table 4.3 Measured showering attributes**

| **Attribute** | **Unit** | **Expression** | **Remark** |
|---|---|---|---|
| (a) $k$ = 0.54-4.05 kPa min$^2$ L$^{-2}$, $T_a$=26.3°C (10 surveyed showerheads) | | | Test for correlation |
| $T_{hot}$ | °C | $36.2 + 1.1\,k$ | <0.001* ($t$-test) |
| $T_{hot}$–$T_{cold}$ | °C | $9.8 + 0.88\,k$ | <0.0001* ($t$-test) |
| $v$ | L min$^{-1}$ | $11.4 - 0.72\,k$ | 0.05*($t$-test) |
| $V$ | L | $60.3 - 6.1\,k$ | 0.05* ($t$-test) |
| $t_s$ | s | $316 - 13\,k$ | 0.4 ($t$-test) |
| (b) $k$ = 2.46 kPa min$^2$ L$^{-2}$, $T_a$=15.8-23.7°C (surveyed WELS rated Grade 2 showerhead) | | | Test for normality |
| $T_{hot}$ | °C | 38.5 (SD=2) | >0.01* ($w/s$ test) |
| $T_{hot}$–$T_{cold}$ | °C | $T_{hot}-10.4T_a^{0.29}$ | $T_{cold}=10.4T_a^{0.29}$ |
| $v$ | L min$^{-1}$ | $v_0\,(k_0/k)^{1/2}$ | Section 4.3 |
| $V$ | L | 45.6 (SD=18.8) | >0.05* ($w/s$ test) |
| $t_s$ | s | 305 (SD=107) | >0.05* ($w/s$ test) |

* Level of significance=0.05 unless otherwise specified; SD = standard deviation

**Table 4.4 Operating parameters of a low flow showerhead, i.e. WELS rated Grade 2 showerhead (*k*=2.46)**

| Group | 1st Month ($T_a$ = 23.7°C) | | | | 2nd Month ($T_a$ = 21.7°C) | | | | 3rd Month ($T_a$ = 16.1°C) | | | | 4th Month ($T_a$ = 16.3°C) | | | | 5th Month ($T_a$ = 15.8°C) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{hot}$ (°C) | $v$ (L min$^{-1}$) | $t_s$ (s) | $V$ (L) | $T_{hot}$ (°C) | $v$ (L min$^{-1}$) | $t_s$ (s) | $V$ (L) | $T_{hot}$ (°C) | $v$ (L min$^{-1}$) | $t_s$ (s) | $V$ (L) | $T_{hot}$ (°C) | $v$ (L min$^{-1}$) | $t_s$ (s) | $V$ (L) | $T_{hot}$ (°C) | $v$ (L min$^{-1}$) | $t_s$ (s) | $V$ (L) |
| 1 | 37.6 | 8.9 | 294 | 43.4 | 37.6 | 8.9 | 294 | 43.4 | 37.6 | 8.5 | 309 | 44.0 | 37.6 | 8.6 | 330 | 47.6 | 37.6 | 8.4 | 316 | 44.1 |
| 2 | 38.9 | 8.4 | 321 | 44.9 | 37.6 | 8.6 | 280 | 40.0 | 37.7 | 8.2 | 292 | 40.1 | 37.7 | 8.3 | 319 | 44.4 | 37.7 | 8.1 | 299 | 40.3 |
| 3 | 35.7 | 11.2 | 299 | 55.8 | 37.7 | 8.3 | 297 | 40.8 | 37.8 | 7.9 | 317 | 41.9 | 37.7 | 8.0 | 341 | 45.8 | 37.8 | 7.8 | 324 | 42.0 |
| 4 | 41.9 | 11.1 | 242 | 44.7 | 37.8 | 8.0 | 302 | 40.3 | 37.9 | 7.7 | 326 | 41.7 | 37.8 | 7.8 | 351 | 45.6 | 37.9 | 7.5 | 332 | 41.5 |
| 5 | 39.0 | 6.3 | 321 | 33.7 | 37.9 | 7.7 | 317 | 40.9 | 37.9 | 7.4 | 340 | 42.0 | 37.9 | 7.6 | 368 | 46.3 | 38.0 | 7.3 | 347 | 41.9 |

### 4.3.2 Maximum flow rate of low flow showerhead

In promoting low flow showerheads, water consumption for an unaltered shower duration is usually assumed to be proportional to the showerhead maximum flow rate (Hong Kong Water Supplies Department 2011a, Toyosada et al. 2013). As described in Section 4.3.1, unaltered shower duration after replacement of low flow showerhead has been demonstrated. According to Equation 3.6 and under same water supply pressure conditions, the maximum flow rate of a low flow showerhead $v$ can be approximated using Equation 4.2, where $v_0$ is the maximum flow rate of the existing showerhead, $k_0$ and $k$ are the resistance factors of the existing (old) and low flow (new) showerheads respectively. The water consumption ratio $v/v_0$ for a shower using the low flow showerhead versus the existing one is therefore proportional to $(k_0/k)^{1/2}$,

$$\frac{v}{v_0} \sim \sqrt{\frac{k_0}{k}} \tag{4.2}$$

As there were variations in usage patterns associated with the newly installed low flow showerhead, the amount of water saved could be less significant. The measured and predicted values of $v/v_0$ for the 10 surveyed washrooms against $(k_0/k)^{1/2}$ are plotted in Figure 4.4. The measured values of $v/v_0$ and $(k_0/k)^{1/2}$ are obtained according to the data listed in Tables 4.2 and 4.4. The predicted values of $v/v_0$ were calculated based on the expression of flow rate $v$ listed in Table 4.3 part (a). Average prediction with error bars are shown for reference. Regression lines in Figure 4.4 show that predicted and measured water use can be correlated with showerhead resistance factor using a constant $c_k$ ($p<0.01$, $t$-test), with expression as Equation 4.3.

$$\frac{v}{v_0} = c_k \sqrt{\frac{k_0}{k}} \tag{4.3}$$

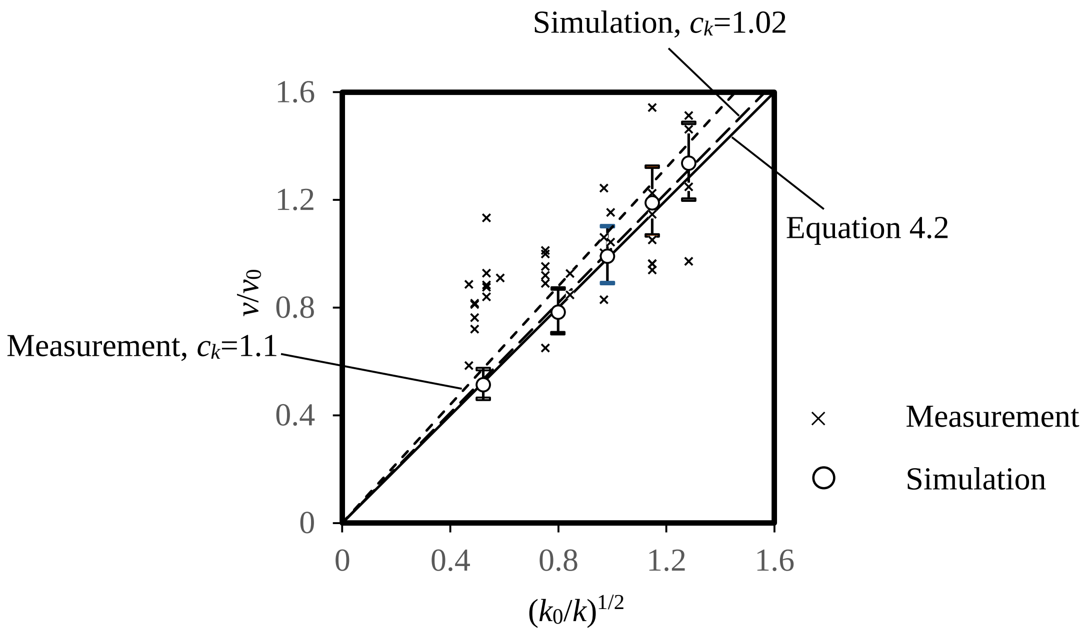



**Figure 4.4 Water consumption ratios for showers**

The results showed that the average maximum water consumption measured was 10% higher than the one predicted by Equation 4.2, i.e. $c_k$ =1.1. The regression indicates that a showerhead with a lower nominal flow rate can improve water efficiency, as outdoor temperature and other parameters contributed to water consumption.

### 4.3.3 User satisfaction and water consumption

It was reported that 22 participants were not satisfied with the flow rate and pressure of the sample low flow showerhead and thus preferred to use their original showerheads. Among the 15 participants who were satisfied with the flow rate and pressure of the low flow showerhead, 8 preferred to use their original showerheads for a more comfortable showering experience while 7 would keep using the low flow showerhead. Figure 4.5 shows the cumulative frequency distribution of occupants' subjective response to the shower flow rate, including satisfaction of flow rate and dissatisfaction of flow rate. The intersection point in Figure 4.5 was found to be 10.8 L $min^{-1}$, which was within the flow rate range of WELS rated Grade 2 showerhead (9 - 12 L $min^{-1}$). As shown in Figure 4.5, when shower flow rate was larger than 10.8 L $min^{-1}$, cumulative frequency of satisfaction increases rapidly, meanwhile the dissatisfaction decreases sharply. Previous study in Taiwan also showed that the preferred shower flow rate by most people was around 8-11 L $min^{-1}$ (Lee et al. 2014).

As shown by Equation 3.5, pressure at showerhead can be quantitatively expressed by shower flow rate using showerhead resistance factor. In the following, only quantitative correlation between occupants' satisfaction of showerhead and shower flow rate was analyzed. The occupants' overall acceptance of showerhead at a flow rate was described by a logistic regression curve, as shown in Figure 4.6. According to Figure 4.6, the proportional constants $C_0$ (= - 4.88) and $C_1$ (= 0.47) for Equation 3.3 were determined. Equation 3.3 gives $\varphi$=0.03-0.97 in a supply flow rate range of 3 to18 L $min^{-1}$.

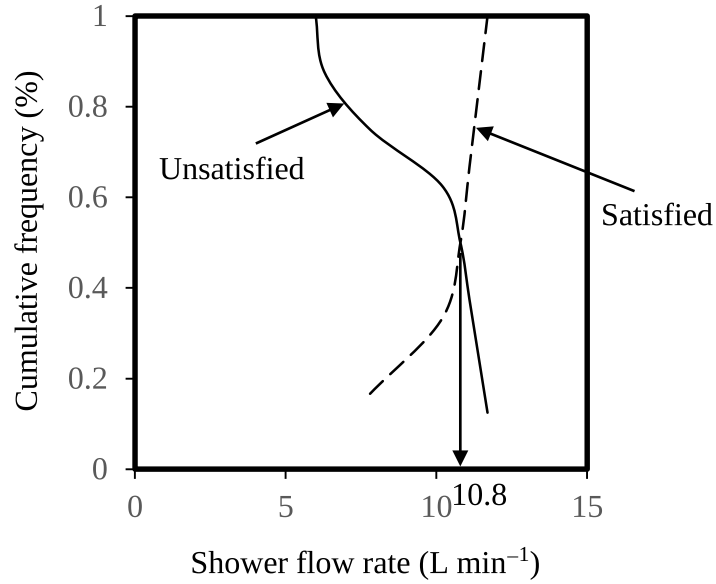



**Figure 4.5 Occupants' acceptance of shower flow rate**

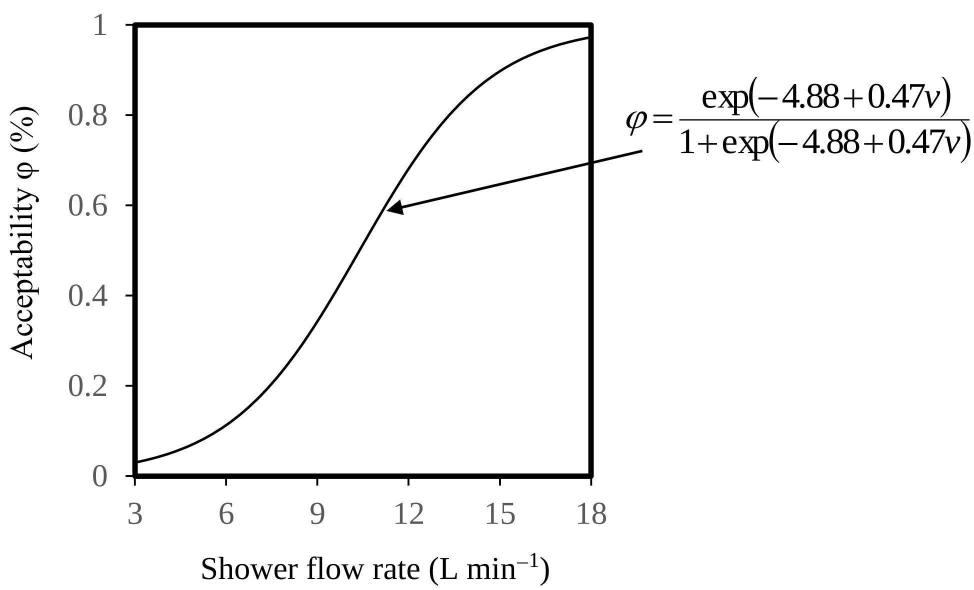



**Figure 4.6 Acceptability of showerhead at a flow rate**

### 4.4 Monte Carlo model validation and simulation results

#### 4.4.1 Model validation

Two reference sources were used for model validation. First, data from a survey conducted by HKWSD, including shower flow rate, daily per capita frequency of showering and duration per shower, as reviewed in Section 2.3.4, were taken as simulation inputs (Hong Kong Water Supplies Department 2011b). According to the survey, 39%, 27%, 22% and 13% of the showerheads currently in use were with flow rates equivalent to WELS rated Grades 1, 2, 3 and 4 respectively (corresponding to mean *k* values of 4.02, 2.26, 1.27 and 0.81 respectively). The predicted average per capita daily consumption as graphed in Figure 4.7(a) is 54.5 L $ps^{-1}$ $d^{-1}$, i.e. 1% lower than the surveyed value (55 L $ps^{-1}$ $d^{-1}$). A very good prediction was made as the result is very close to the reference line of HKWSD measured water consumption.

In addition, the annual amount of domestic hot water energy consumed (water used in cooking excluded) in Hong Kong reported by HKEMSD was taken as a reference (i.e. 8.3 GJ $ps^{-1}$ $yr^{-1}$×19%=1.577 GJ $ps^{-1}$ $yr^{-1}$, as reviewed in Section 2.2) (Hong Kong Electrical and Mechanical Services Department 2015). Based on the data from HKWSD (Hong Kong Water Supplies Department 2011b), the predicted energy consumption for heating hot water for September to May is 1.1 GJ $ps^{-1}$ $yr^{-1}$ (sd=0.09 GJ $ps^{-1}$ $yr^{-1}$), a 30% below the HKEMSD reference value (i.e. 1.577 GJ $ps^{-1}$ $yr^{-1}$) and the reference line for the energy consumption. Based on the year-round showering patterns of Hong Kong residents from open literature data (Hong Kong Water Supplies Department 2011b), the predicted energy consumption for heating hot shower water is 1.66 GJ $ps^{-1}$ $yr^{-1}$; and as shown in Figure 3.1(b), it is 5% higher than the HKEMSD reference.

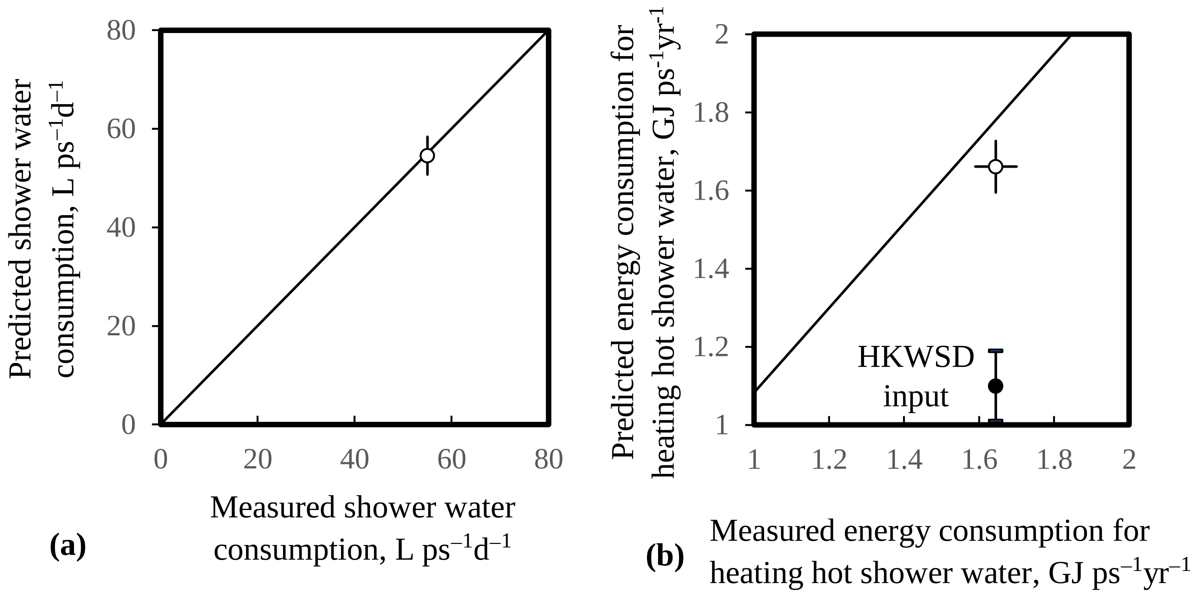



**Figure 4.7 Model validation: (a) Per capita daily shower water consumption; (b) Per capita annual hot shower water energy consumption**

### 4.4.2 Simulation results of shower water consumption as well as associated energy use and corresponding $CO_2$ emissions

Simulated shower water consumption and associated energy consumption for heating hot shower water for low flow showerheads, i.e. WELS rated showerheads, are exhibited in Table 4.5. The simulations in Table 4.5 is for uniform distribution, and the limit of showerhead resistance factor is determined. It should be noted that for resistance factor $k$>4.2, the showerhead will be the Grade 1. The average maximum water consumption range is 15.4-41 $m^3$ $ps^{-1}$ $year^{-1}$ while the average range of maximum energy consumption for heating hot shower water is 1.24-2.44 GJ $ps^{-1}$ $yr^{-1}$. The maximum shower water consumption is proportional to the maximum showerhead flow rate. In real shower practice, the showerhead flow rate is limited by this maximum showerhead flow rate, meanwhile subject to user's adjustment.

**Table 4.5 Predicted water and energy consumption results for low flow showerheads, i.e. WELS rated showerheads**

| **Showerhead** | **Resistance factor range** | **Water consumption ($m^3$ $ps^{-1}$ $yr^{-1}$)** | **Energy consumption for heating hot water (GJ $ps^{-1}$ $yr^{-1}$)** |
|---|---|---|---|
| WELS Grade 1 | 4.02-9.04 | 15.4 (0.8) | 1.24 (0.09) |
| WELS Grade 2 | 2.26-4.02 | 23.5 (1.3) | 1.63 (0.12) |
| WELS Grade 3 | 1.27-2.26 | 31.8 (1.7) | 2.00 (0.15) |
| WELS Grade 4 | 0.81-1.27 | 41.0 (2.2) | 2.44 (0.18) |

Table 4.6 presents the impacts of low flow showerheads for bathing on shower water savings, energy savings and $CO_2$ emissions reductions. For the existing showerheads, based on the energy requirement of per capita hot shower that 114 MJ $ps^{-1}$ $yr^{-1}$ for water treatment and supply, and 1.66 GJ $ps^{-1}$ $yr^{-1}$ for heating, the estimated value of $CO_2$ emissions is 384 kg-$CO_2$ $ps^{-1}$ $yr^{-1}$. This estimate is equivalent to $2.76\times10^9$ kg-$CO_2$ $yr^{-1}$ for a population of 7.188 million in Hong Kong by the end of 2013. Scenarios for $k\geq1.27$, 2.26 and 4.02 are shown in the table (corresponding to installation of WELS rated Grades 1-3, Grades 1-2 and Grade 1 showerheads respectively) and the results indicate that full installation of low flow showerheads of WELS rated ones with $k\geq4.02$ ($\leq$ 9 L $min^{-1}$) (WELS rated Grade 1 showerhead) can reduce shower water consumption by 37%, energy consumption by 25% and $CO_2$ emissions by 26%. The evaluation results give the theoretically maximum benefits of low flow showerheads for bathing in the limiting case, which can be a reference for the evaluation of the real impact of low flow showerheads for bathing as well as for policy adjustment and making. Compared with the engineering estimation in open literature that three star rated water efficient showerheads (6 or 7 L $min^{-1}$) generate about 25% of shower water saving under the Water Efficiency Labelling and Standards (WELS) scheme in Australia (Australian Government 2017b), the shower water reduction (37%) estimated by Monte Carlo simulation for the limiting case in this study was greater.

**Table 4.6 Impacts of low flow showerheads for bathing on shower water savings, energy savings and $CO_2$ emission reductions**

| Scenario | Water consumption ($m^3$ $ps^{-1}$ $yr^{-1}$) | Energy consumption for heating hot water (GJ $ps^{-1}$ $yr^{-1}$) | $CO_2$ emissions (kg-$CO_2$ $ps^{-1}$ $yr^{-1}$) |
|---|---|---|---|
| Existing: $k$=0.81-9.04 (mean=3.8, sd=1.74) | 24.3 | 1.66 | 384 |
| (1) For $k \geq 1.27$ | 21.0 (–14%) | 1.50 (–10%) | 345 (–10%) |
| (2) For $k \geq 2.26$ | 17.5 (–28%) | 1.35 (–19%) | 309 (–20%) |
| (3) For $k \geq 4.02$ | 15.4 (–37%) | 1.24 (–25%) | 283 (–26%) |

### 4.5 Summary

Survey and measurement results were given and discussed first. It showed that the surveyed situations of hot showers (in contrast with cold showers) and shower frequency were consistent with previous studies. Besides, there was no significant difference between surveyed and measured values for hot shower temperature and showerhead operating time, which might indicate that users have the sense of shower water temperature and shower time; this provides the possibility of water conservation by residents' active behavior changes by education campaigns. Water consumptions with the maximum showerhead flow rate and user preferred showerhead flow rate were discussed respectively, and the expression of user acceptance of showerhead by user preferred showerhead flow rate was given. Strong associations with showerhead resistance factor *k* were reported for hot shower temperature, temperature difference between hot and cold water supply, flow rate and water consumption, but not for shower duration.

The Monte Carlo simulations shows that the average shower water consumption with the existing showerheads was 24.3 $m^3$ $ps^{-1}$ $yr^{-1}$ while the average energy consumption for heating hot shower water was 1.66 GJ $ps^{-1}$ $yr^{-1}$ and the average $CO_2$ emissions was 384 kg-$CO_2$ $ps^{-1}$ $yr^{-1}$. The simulation results also indicated that full installation of low flow showerheads of WELS rated ones with $k \geq 4.02$, namely the most water efficient showerheads, can reduce water consumption by 37%, energy use by 25% and $CO_2$ emissions by 26%.

As shown by the simulation results, large percentage of water consumption (i.e. 37%) can be saved while using the most water efficient showerheads. For the adoption of low flow showerheads in high-rise buildings, the total water consumption of showering may reduce greatly. The influence of the low flow showerheads for bathing in relation to the design flow rate of water supply system in buildings will be given in following Chapter 5.

# Chapter 5

# Impact of low flow showerheads for bathing on design flow rate of water supply systems in buildings

## 5.1 Introduction

Great reduction of per capita shower water consumption (i.e. 37% reduction) has been identified in Chapter 4 as the low flow showerheads for bathing. The impact of shower water consumption reduction on the design flow rate of water supply system is discussed in this chapter. Monte Carlo simulation results of water demand time series for each type of appliances, including showerhead, wash basin, kitchen sink and washing machine, in a case building are given. Following, the simulated design flow rate of water supply system in two cases (Case A: all appliances are conventional ones; Case B: showerheads are low flow ones, while other types of appliances are conventional ones) are presented. The redesign of inflow rate for the limiting case that with full installation of the most water efficient showerheads, i.e. WELS rated Grade 1 showerheads, in water supply system is discussed and suggestions are given.

## 5.2 Simulated water demand time series

Figures 5.1-5.5 show the simulation results of the time series of demand flow rates $q_w(t)$ for each type of appliances using Equation 3.20 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 100 years operations is an approximate value which is determined based on that no significant difference of simulation results occurs with the increase of the operation years. Some design guides suggest 1% failure rate for design demand flow rate (Ingle et al. 2014), therefore 1 out of 100 years was taken as a reference calculation in this study. The time step of the daily demand time series is 1 s.

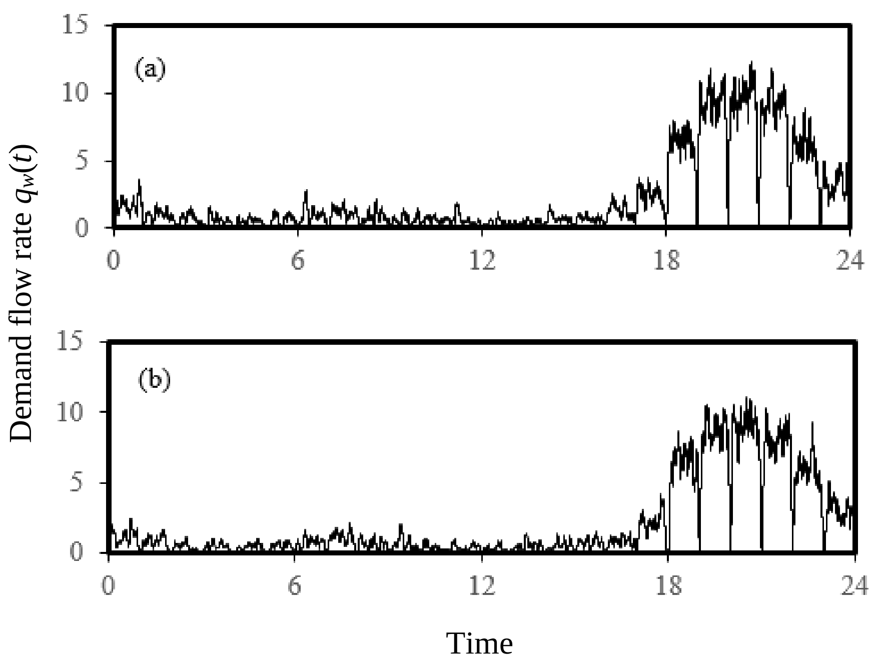



**Figure 5.1 Example demand flow rates for 600 conventional showerheads: (a) maximum daily consumption (202.1 $m^3d^{-1}$); (b) minimum daily consumption (180.0 $m^3d^{-1}$)**

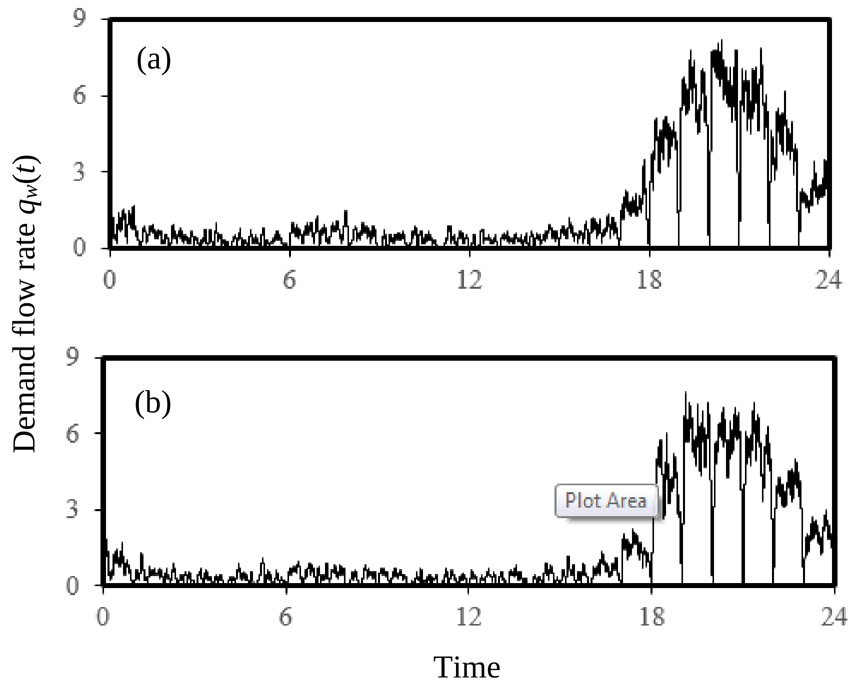



**Figure 5.2 Example demand flow rates for 600 low flow showerheads, i.e. WELS rated Grade 1 showerheads: (a) maximum daily consumption (132.8 $m^3d^{-1}$); (b) minimum daily consumption (119.5 $m^3d^{-1}$)**

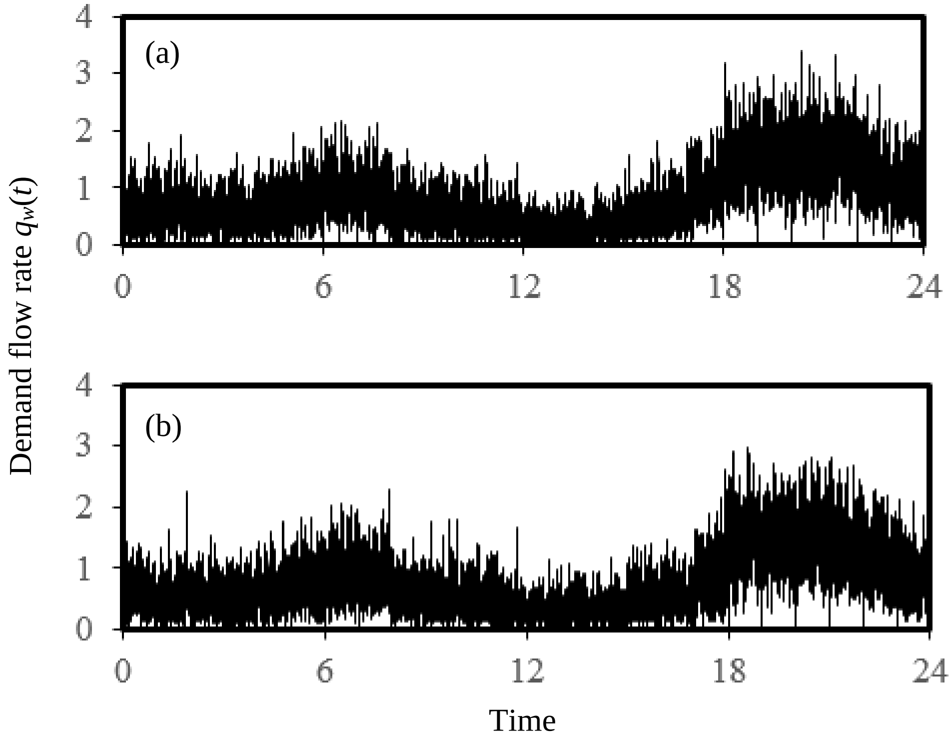



**Figure 5.3 Example demand flow rates for 600 wash basins: (a) maximum daily consumption (68.0 $m^3d^{-1}$); (b) minimum daily consumption (64.6 $m^3d^{-1}$)**

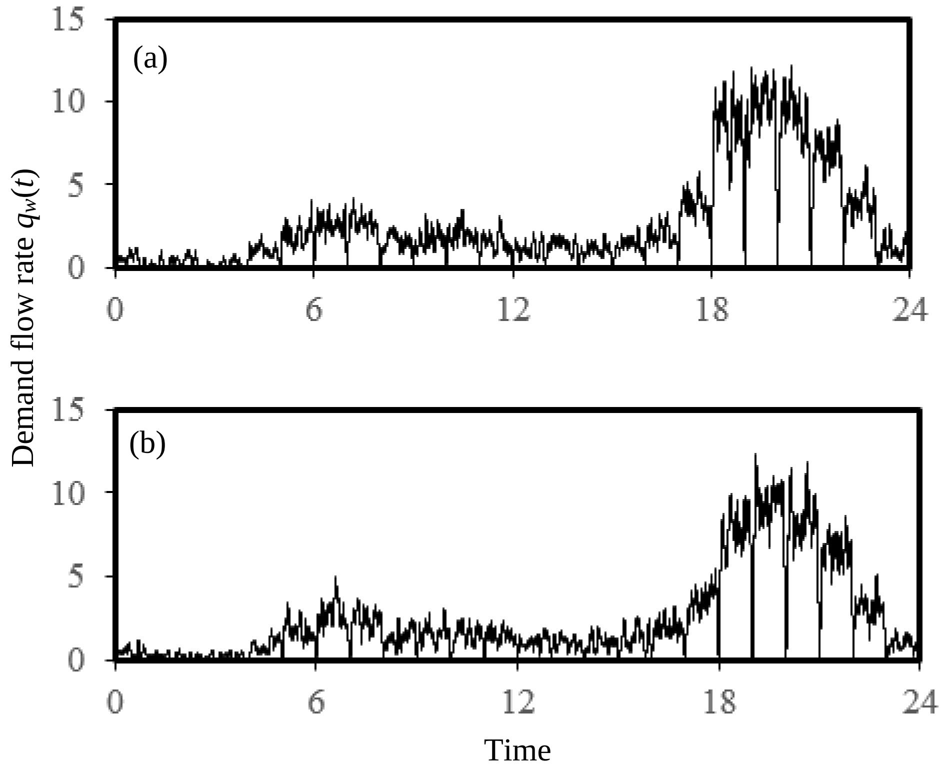



**Figure 5.4 Example demand flow rates for 600 kitchen sinks: (a) maximum daily consumption (226.9 $m^3d^{-1}$); (b) minimum daily consumption (208.0 $m^3d^{-1}$)**

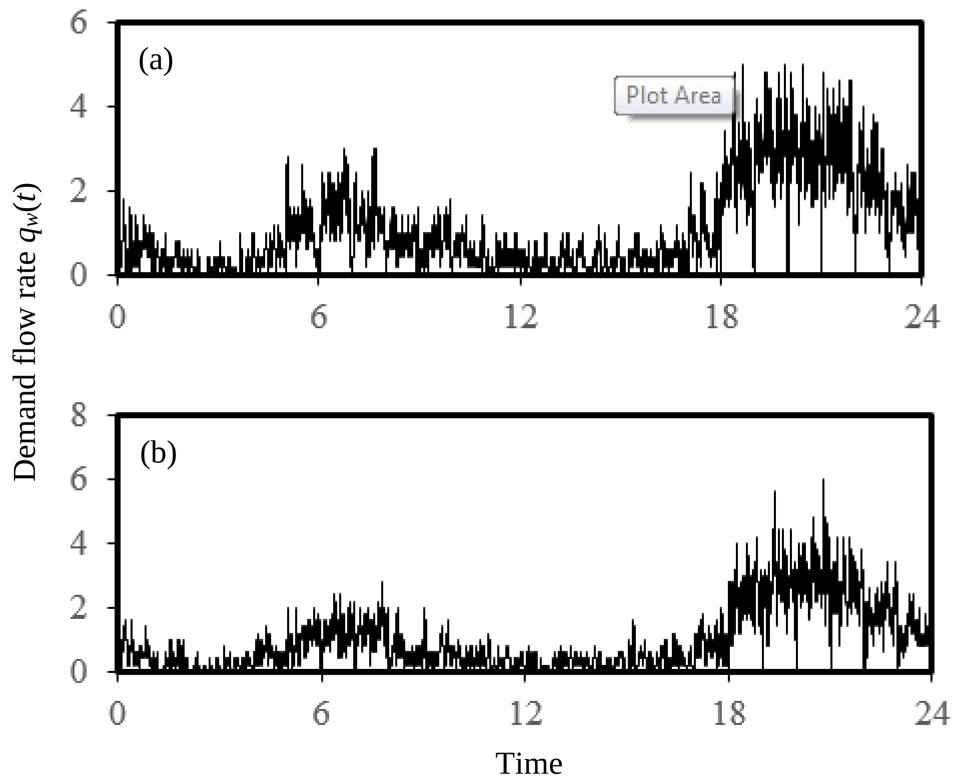



**Figure 5.5 Example demand flow rates for 600 washing machines: (a) maximum daily consumption (93.1 $m^3d^{-1}$); (b) minimum daily consumption (82.4 $m^3d^{-1}$)**

The time series of total demand flow rates for all types of appliances for Case A (all appliances are conventional ones) and Case B (showerheads are low flow ones, i.e. WELS rated Grade 1 showerheads, while other types of appliances are conventional ones) are shown in Figure 5.6 and Figure 5.7 respectively.

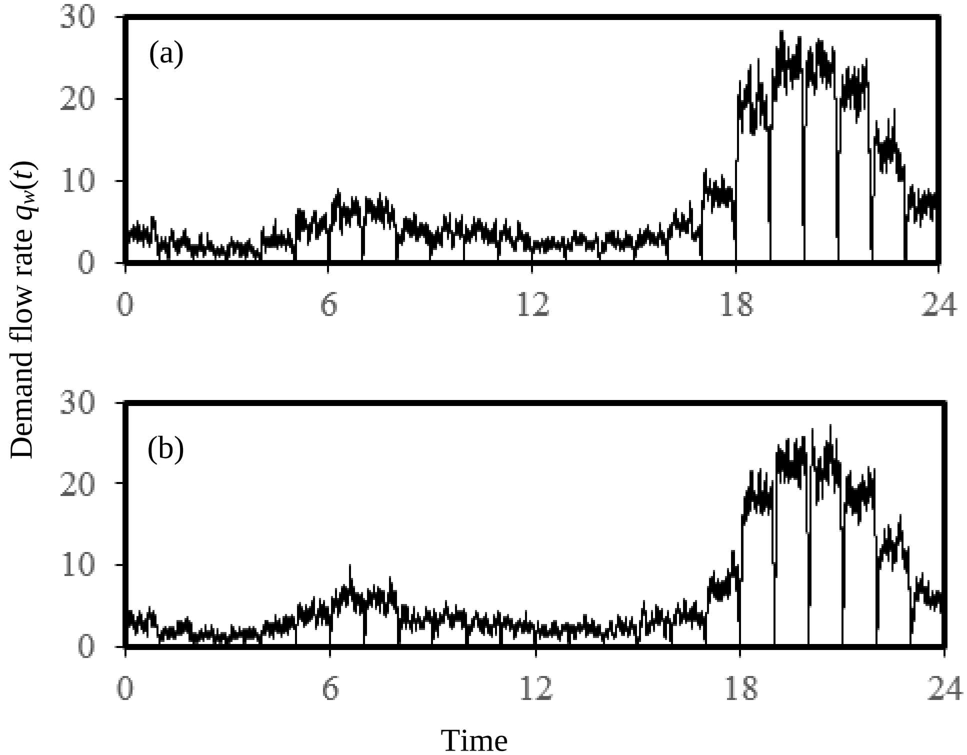



**Figure 5.6 Total demand flow rates for Case A (all appliances are conventional ones): (a) maximum daily consumption (590.0 $m^3d^{-1}$); (b) minimum daily consumption (534.8 $m^3d^{-1}$)**

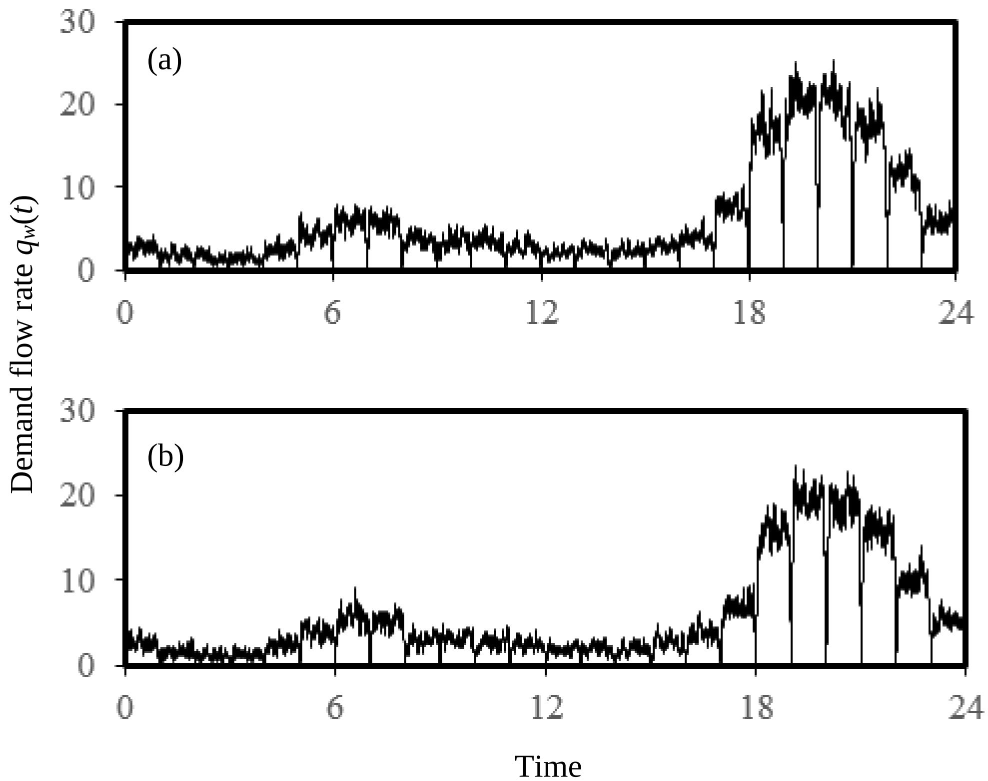



**Figure 5.7 Total demand flow rates for Case B (showerheads are low flow ones, i.e. WELS rated Grade 1 showerheads, while other types of appliances are conventional ones): (a) maximum daily consumption (520.7 m$^3$d$^{-1}$); (b) minimum daily consumption (474.4 m$^3$d$^{-1}$)**

The daily water consumptions were acquired by sum of the demand flow rate along the time series shown in Figure 5.1-5.7 respectively. Results in Figure 5.6 indicated that the simulated daily consumption range for Case A was from 534.8 m$^3$d$^{-1}$ to 590.0 m$^3$d$^{-1}$, with an average of 562.4 m$^3$d$^{-1}$; with low flow showerheads of WELS rated Grade 1 ones, the simulated daily consumption range was from 474.4 m$^3$d$^{-1}$ to 520.7 m$^3$d$^{-1}$, with an average of 497.6 m$^3$d$^{-1}$, as shown in Figure 5.7. Water consumption reduction of about 11% was shown after full installation of low flow showerheads of WELS rated Grade 1 ones in water supply system. While in previous studies which water use was evaluated on household level, 3% - 8% water reduction was indicated as the use of low flow showerheads (Renwick and Archibald 1998, Price et al. 2014).

The Monte Carlo simulation in Chapter 4 shows that the yearly shower water consumption per capita with existing showerheads was 24.3 $m^3$ $ps^{-1}$ $yr^{-1}$, equal to average 0.067 $m^3$ per capita per day (24.3 $m^3$ $ps^{-1}$ $yr^{-1}$/365 days). Assuming the 600 showerheads are installed in 600 households, and maximum occupant load in each household is 4.2 (the same setting of the parameter values as in the above Monte Carlo simulation of shower demand time series), the daily total shower water consumption 168.8 $m^3d^{-1}$ (=0.067×600×4.2) in average was acquired; compared with the value obtained from above simulation of shower demand time series with conventional showerheads (e.g. (202.1+180.0)/2=191.1 $m^3d^{-1}$ ), no significant difference (11.7% difference) was shown by the Monte Carlo simulations with the two models. This can be the validation of the models for demand time series.

### 5.3 Simulated design flow rate of water supply system

Figures 5.10 and 5.11 illustrate the solution pairs ($V_o$, $q_o$) given by Equation 3.18 for the demand time series shown in Figures 5.6 and 5.7 respectively with respect to integration time periods $\tau_o$=10, 60 and 300s. As the simulated solution pairs with integration time period $\tau_o$= 1s for WC demand in previous study showed no significant difference from that with integration time period $\tau_o$= 10s (Wong et al. 2014a), the minimum integration time period $\tau_o$= 10s was chosen in this study. As shown in Figures 5.8 and 5.9, a coarse integration time period $\tau_o$ (e.g. 300s) for the simulation may not give an accurate solution for small storage volume, i.e. the simulated inflow rate with $\tau_o$= 300s was greatly lower than that with $\tau_o$= 10s and $\tau_o$= 60s, however, no significant difference was found for the solutions for large storage volume.

For Hong Kong practice, the storage capacities of water tanks (including sump tank and roof tank, and the proportion of capacity of sump tank to roof tank is 1:3) is suggested to be 135 liters per flat up to 10 flats; for more than 10 flats, 90 liters for each additional flat (Hong Kong Water Supplies Department 2014). Assuming the simulated 600 showerheads are installed in 600 flats, correspondingly roof tank volume of 40838L (= $3/4(135\times 10+90\times 590)$) can be acquired. At the storage volume of 40838 L, the simulated inflow rates for Case A was 17.9 $Ls^{-1}$ in Figure 5.8(a) and was 16.4 $Ls^{-1}$ in Figure 5.8(b). These inflow rates (e.g. 17.9 $Ls^{-1}$ or 16.4 $Ls^{-1}$) do not pose significant practical concerns about specifying the inflow rates required for general engineering applications as safety margins (about 30%) are normally imposed when selecting a water pump to feed the storage tank. Figure 5.9(a) and 5.9(b) showed that the simulated inflow rates for Case B were 15.1 $Ls^{-1}$ and 13.8 $Ls^{-1}$ respectively. Reduced inflow rate (reduction of 15%) was shown for Case B when compared that for Case A, which was due to the water consumption reduction (reduction of 11%) of low flow showerheads for bathing. The minimum inflow rates for the cases shown in Figures 5.8(a) and 5.8(b) were 6.8 $Ls^{-1}$ and 6.2 $Ls^{-1}$ respectively; for the cases shown in Figures 5.9(a) and 5.9(b), the minimum inflow rates were 6.0 $Ls^{-1}$ and 5.5 $Ls^{-1}$ respectively.

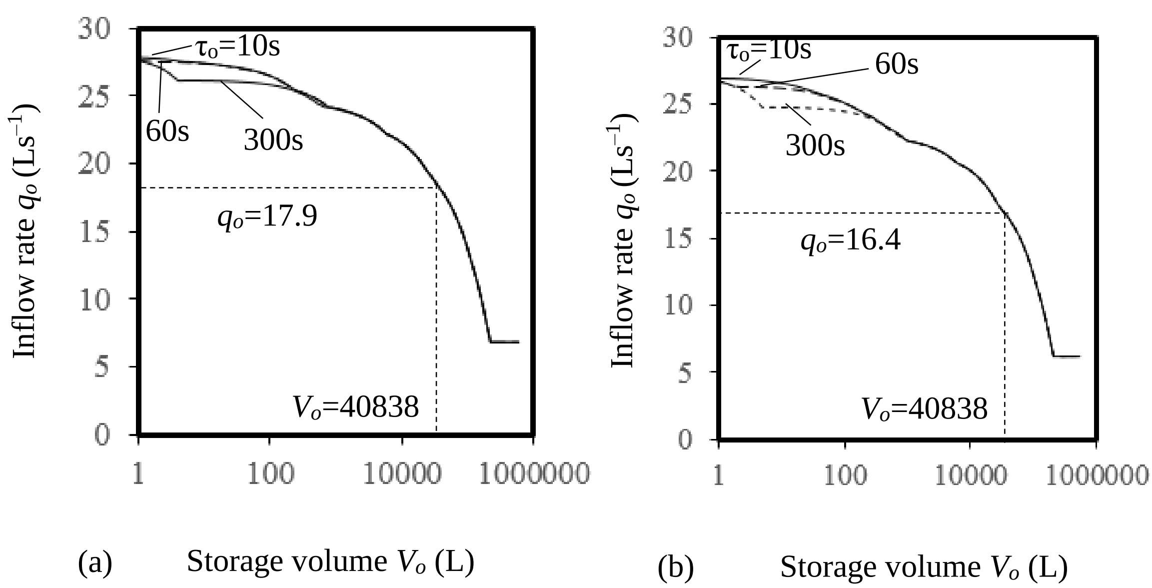
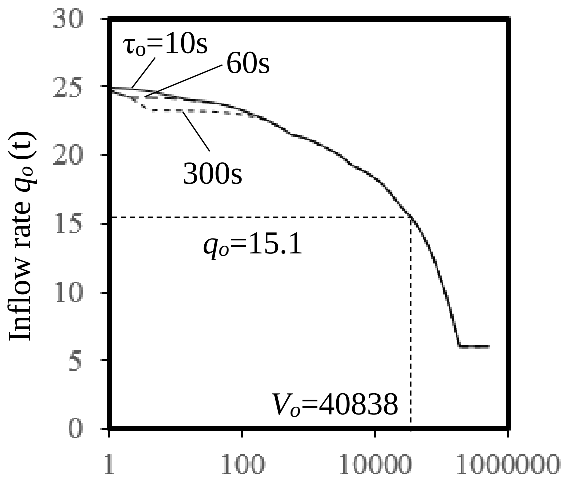
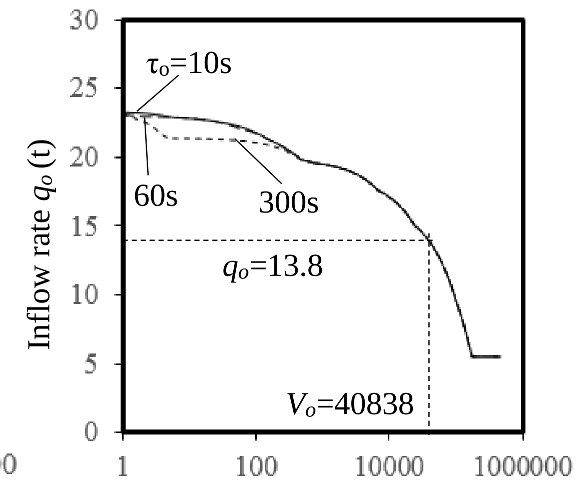



**Figure 5.8 Solutions of inflow rate and storage volume for Case A: (a) for the maximum demand time series in Figure 5.6(a); (b) for the minimum demand time series in Figure 5.6(b)**




(a) Storage volume $V_o$ (L) (b) Storage volume $V_o$ (L)

**Figure 5.9 Solutions of inflow rate and storage volume for Case B: (a) for the maximum demand time series in Figure 5.7(a); (b) for the minimum demand time series in Figure 5.7(b)**

## 5.4 Energy efficiency evaluation of water supply systems with different design flow rates

An example of high-rise roof tank water supply system for appliances including showerheads, wash basins, kitchen sinks and washing machines (in which each type of appliances is with installation number of 600) is presented in Table 5.1, with schematic drawing shown in Figure 3.5. Roof tank volume of 40838 L (41 $m^3$) was adopted, and daily water consumption and inflow rate of up-feed pipe were determined based on simulation results shown in Figures 5.6-5.9. According to the design practice that water velocity in up-feed pipe of water supply system is generally designed in the range from 1 to 2 m $s^{-1}$, also kept below 3 m $s^{-1}$ to prevent the effect of water hammering, the roof tank in this study was fed by a pump at the design flow rate through a 108-mm-diameter pipe. The total static head for $h_l$=100 m was counted and a friction head loss $H_f$ for an equivalent pipe length $h_{fo}$=150 m was included. Friction loss of per meter run was obtained from pipe sizing chart in Plumbing Engineering Services Design Guide (The Institute of Plumbing 2002), as shown in Figure 5.10; the values of friction loss of per run for Case A and Case B were 0.037 meters per meter run and 0.027 meters per meter run respectively. Then multiplied by the equivalent pipe length $h_{fo}$, finally $H_f$ =5.55 m and 4.05 m were acquired for Case A and Case B respectively. Besides, an average height of demand locations $h_d$=50 m and an overall pump efficiency $\eta_{ov}$=0.5625 were applied. Assuming the desired minimum water pressure head at the roof tank inlet $H_o$=0, the energy efficiency of the example water supply system was calculated by Equation 3.33, and summarized in Table 5.1. Water velocity in the feed pipe was obtained from design inflow rate divided by pipe cross-section area.

Table 5.1 shows that with reduced inflow rate of up-feed pipe in Case B with low flow showerheads for bathing, the system energy efficiency can increase from 0.266 to 0.270, corresponding to an efficiency increase of 1.5%. It is the result of a lower friction head loss in the pipelines as the lower water velocity in up-feed pipe than that in Case A with conventional showerhead demands. However, the efficiency increase was slight. This was due to the low value (0.008-0.1, as shown by the left vertical coordinate in Figure 5.11) of d'Arcy friction factor $\lambda$ expressed in Equation 3.30, which weakens the influence of flow velocity on friction loss in pipelines.

Using the daily water consumption $V_\infty$ and daily pumping energy $E_{pump}$, the energy consumption intensity of water (kWh m$^{-3}$) at the stage of pumping water inside buildings were calculated, and results were 0.512 kWh m$^{-3}$ and 0.504 kWh m$^{-3}$ for Case A and Case B respectively. No significant difference of energy consumption intensity of water was found, so that $CO_2$ emission factors for water at the stage of pumping water inside buildings were also similar for Case A and Case B.

However, still 13% (35-39 kWh) of daily pumping energy was reduced, which was due to the great reduction of water consumption of low flow showerheads for bathing. For the yearly operation of the pumping system, 12.8-14.2 MWh energy of pumping water inside buildings could be saved of low flow showerheads for bathing; taking $CO_2$ emission factor to be 0.78 kg-$CO_2$ kWh$^{-1}$, correspondingly 9.98-11.08 tons of $CO_2$ emission could be reduced.

**Table 5.1 An example of high-rise roof tank water supply system**

| Parameters | Case A | Case B |
|---|---|---|
| Total tank size ($m^3$) $V_o$ | 41 | 41 |
| Daily consumption ($m^3$) $V_\infty$ | 535-590 | 474-521 |
| Design inflow rate ($Ls^{-1}$) $q_o$ | 17.9 | 15.1 |
| Feed pipe water velocity ($ms^{-1}$) $v_o$ | 1.95 | 1.60 |
| Friction head loss (m) $H_f$ | 5.55 | 4.05 |
| System energy efficiency $\alpha_t$ | 0.266 | 0.270 |
| Total electricity power (kW) $P_t$ | 1.77 | 1.09 |
| Daily pumping energy (kWh) $E_{pump}$ | 274-302 | 239-263 |

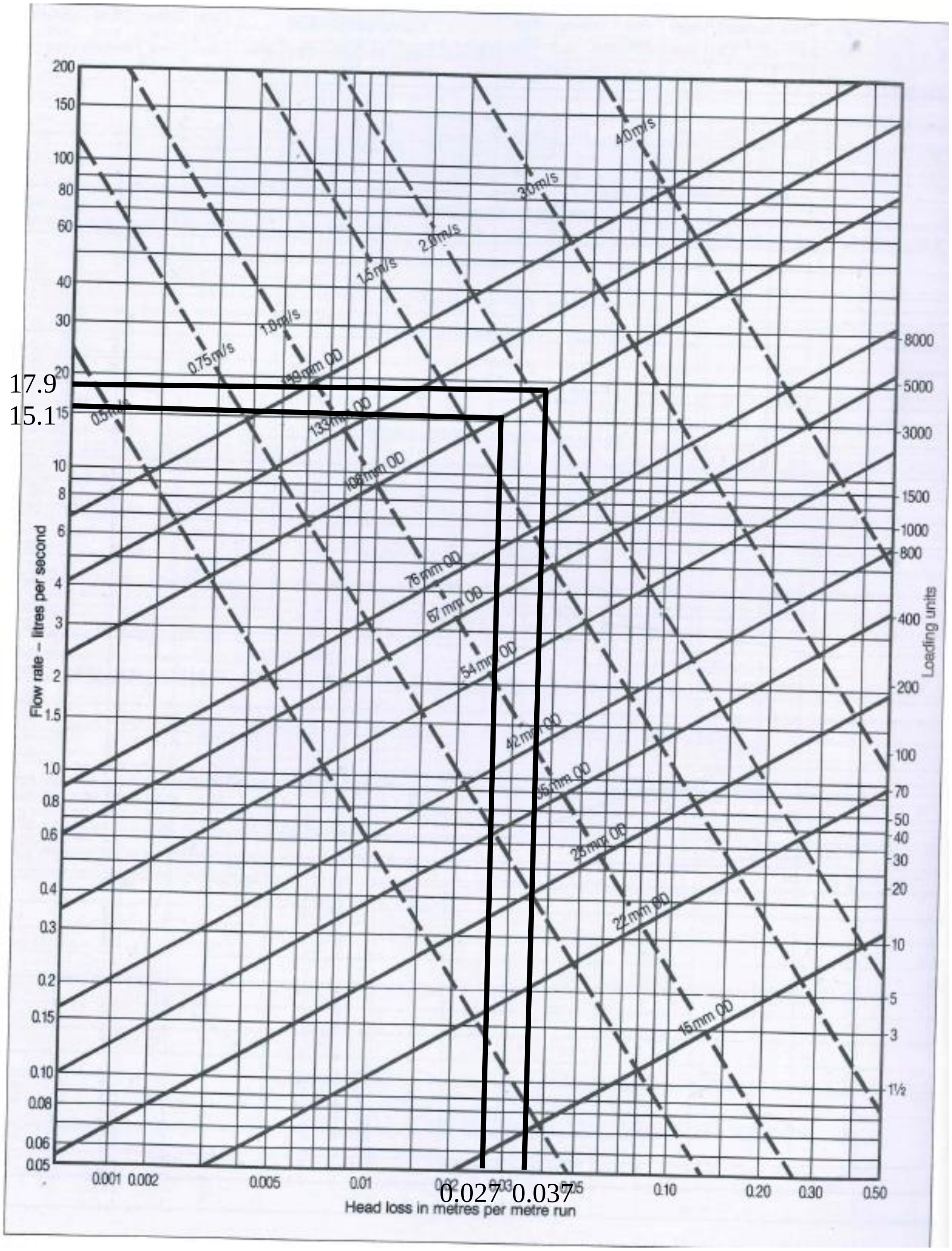



**Figure 5.10 Pipe sizing chart – copper and stainless steel (The Institute of Plumbing 2002)**

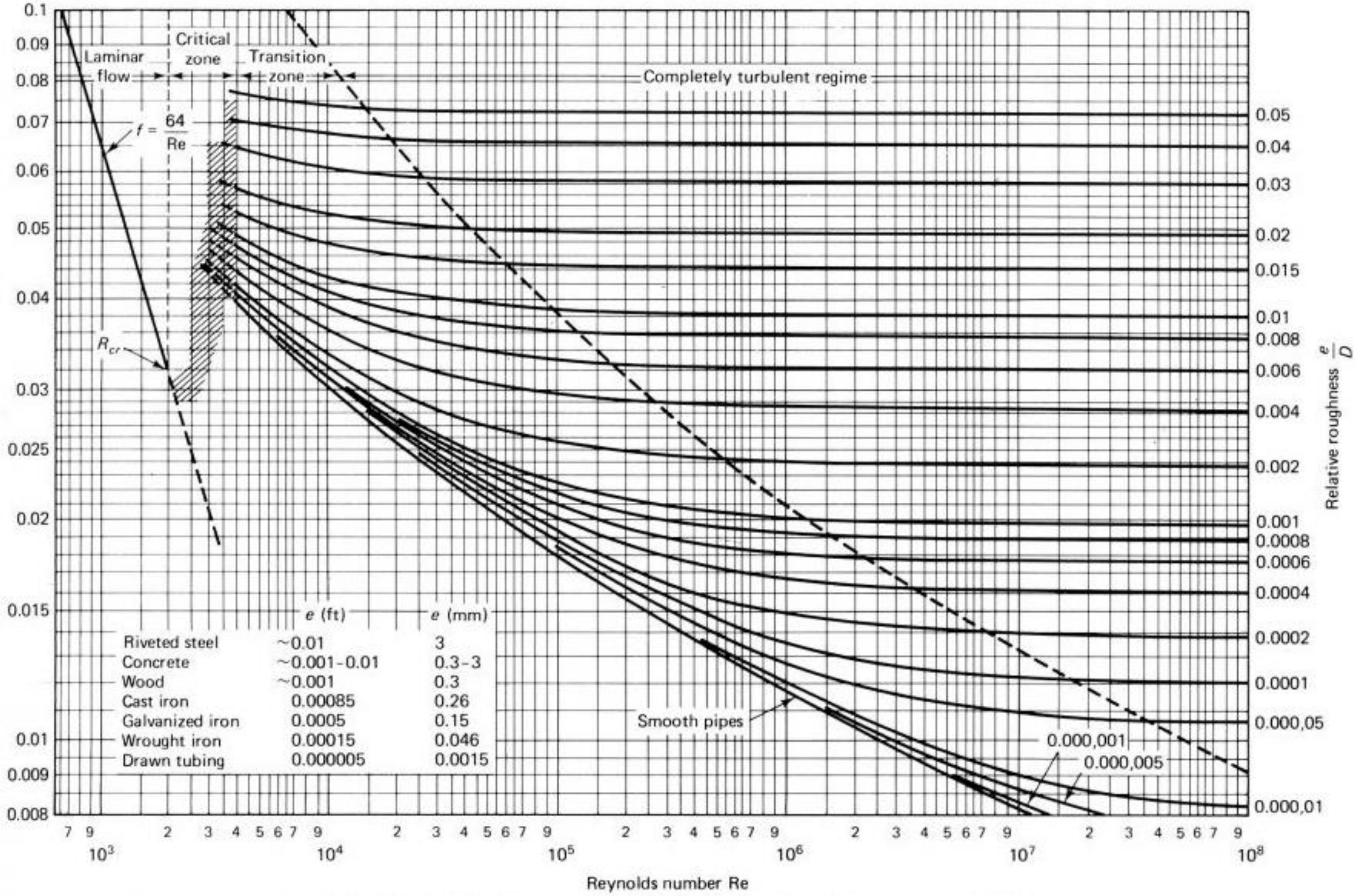



**Figure 5.11 Moody diagram (Moody 1944) for selection of d'Arcy friction factor**

### 5.5 Summary

The design flow rates of up-feed pipe in roof tank water supply systems of Case A (all types of appliances are conventional ones) and Case B (showerheads are low flow ones, i.e. WELS rated Grade 1 showerheads, while other types of appliances are conventional ones) were given by Monte Carlo simulations respectively. It shows that the design flow rates in Case A were 16.4-17.9 $Ls^{-1}$, while in Case B with low flow showerheads, the design flow rates were 13.8-15.1 $Ls^{-1}$. Reduced design flow rate (reduction of 15%) was shown for Case B when compared that for Case A, which was due to the water consumption reduction (reduction of 11%) of low flow showerheads for bathing. With unaltered pipe diameter, lower inflow rate in the up-feed pipe of the water supply system leads to lower friction head loss in the pipelines. Improved energy efficiency was identified with the lower design flow rate after installation of low flow showerheads in the water supply system, i.e. energy efficiency of the water supply system increased from 0.266 (in Case A) to 0.270 (in Case B). As the energy efficiency improvement of the water supply system was slight (i.e. only 1.5%), the energy consumption intensity of pumping water inside buildings were similar for systems with conventional showerheads and low flow showerheads. However, still 13% (35-39 kWh) of daily pumping energy can be saved as the great reduction of daily shower water consumption as low flow showerheads for bathing. For the yearly operation of the pumping system, 12.8-14.2 MWh pumping energy can be saved and 9.98-11.08 tons of $CO_2$ emissions can be reduced as the low flow showerheads for bathing with WELS rated Grade 1 showerheads.

The results showed that energy efficiency of water supply system did increase while reducing the inflow rate of up-feed pipe with unaltered pipe diameter when with low flow showerheads for bathing, however, the efficiency increase was slight. From the energy efficiency aspect, the results revealed the unnecessity of redesign of inflow rate of up-feed pipe after only installation of low flow showerheads in water supply systems. For the situation with full installation of all types of water efficient appliances, the redesign of inflow rate of up-feed pipe need to be studied further.

# Chapter 6

# Aerosol generation rate of low flow showerheads

## 6.1 Introduction

The impacts of low flow showerheads for bathing in relation to the shower water consumption, energy use and $CO_2$ emissions, as well as on design flow rate of water supply system have been analyzed in the last two chapters. In this chapter, aerosol generation rate of low flow showerheads is discussed. First, four sample showerheads for chamber test of aerosol generation and its physical properties and spray attributes are presented. Then, results of the experimental study and CFD simulations of aerosol generation of showerheads in the chamber are given. Following, aerosol mass generation rates of the four sample showerheads are calculated based on the experimental and CFD simulation results, and correlations with showerhead physical properties and spray attributes are discussed. Moreover, aerosol generation rate of low flow showerheads is analyzed.

## 6.2 Sample showerheads for aerosol generation test

Figure 6.1 shows the four sample showerheads adopted in this study for aerosol generation test. The physical properties of these showerheads are summarized in Table 6.1. It is noted for the samples 1 and 2 are conventional showerheads, and samples 3 and 4 are low flow showerheads, i.e. WELS rated Grade 1 showerheads with reduced nominal flow rates (Hong Kong Water Supplies Department 2011a). The resistance factor $k$ of four sample showerheads was determined by the measured water flow rates under pressure range of 50-250 kPa. The choice of the four sample showerheads fit for the timeframe of the experiment, and the selected samples covers a wide range of primarily operating characteristics, e.g. pressure, resistance factor $k$ and flow rate. It should be noted that Grade 1 showerheads still get a wide range of products. The experiment here is intent to cover a wider range of conditions, therefore the choice of the sample showerheads is as this. The nozzle area ratio $\phi_A$ is expressed by the total nozzle area $A_s$ (m$^2$) on the showerhead faceplate divided by the faceplate area $A_f$ (m$^2$),

$$\phi_A = \frac{A_s}{A_f} \tag{6.1}$$

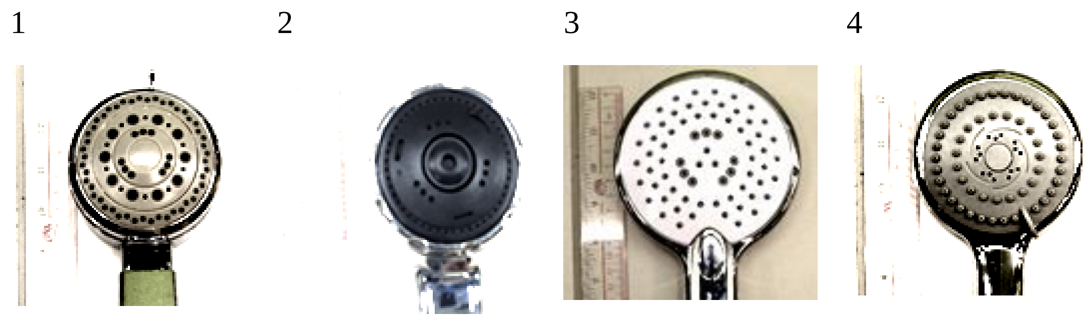


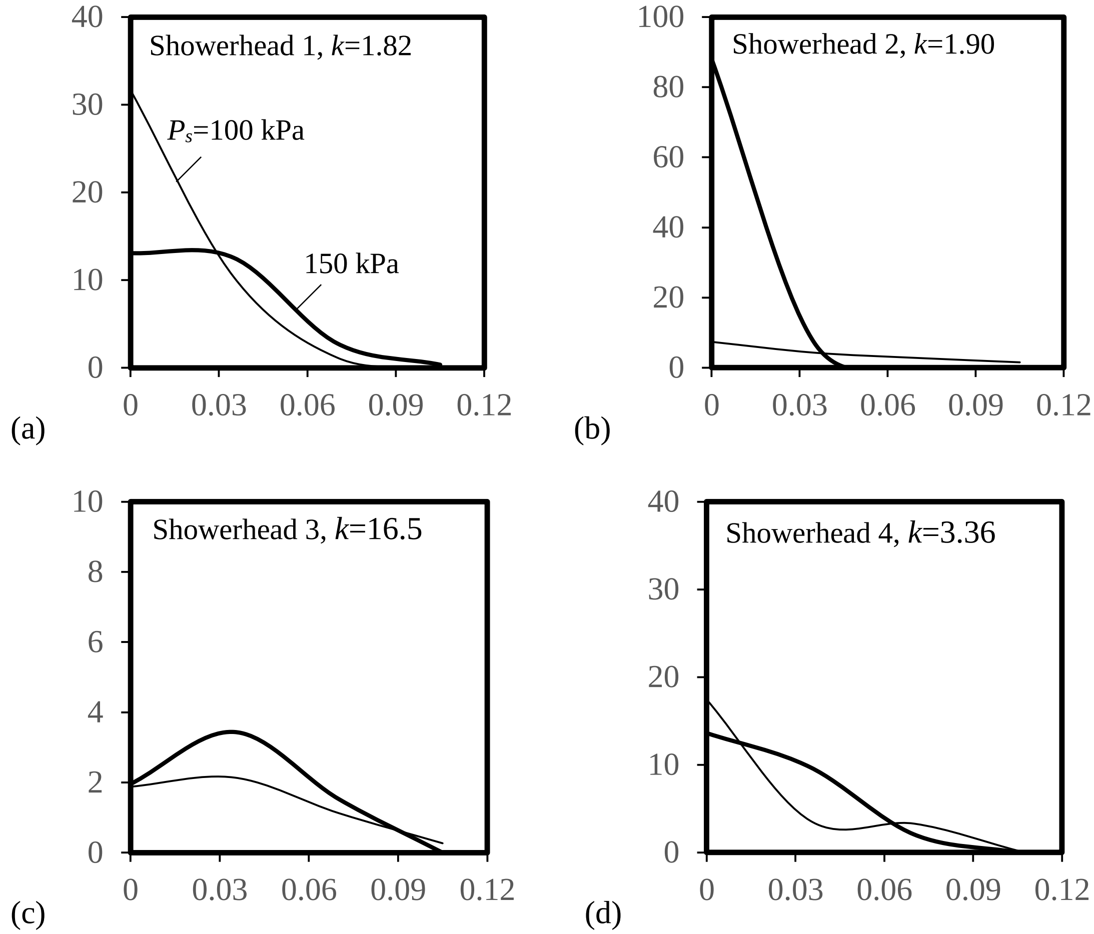

**Figure 6.1 Sample showerheads**

Figure 6.2 shows the mass flux density ($u_{s,d}$) measurement results for the four sample showerheads. Although Showerheads 1 and 2 had similar resistance factors (i.e. 1.82 and 1.90 kPa $\text{min}^2$ $\text{L}^{-2}$ respectively), they had very different water discharge patterns. For a water supply pressure varied from 100 kPa to 150 kPa, Showerhead 1 gave a concentrated mass flux in the near axial distance at a lower pressure and a more evenly distributed mass flux over the spray coverage at a higher pressure while Showerhead 2 gave opposite results. Using the absolute gradient $\phi_u^{'} = \left|\frac{d\phi_u}{dP}\right|$ to indicate the pressure sensitivity of the water distribution patterns, the distribution patterns of the WELS rated Showerheads 3 and 4 ( $\phi_u^{'}$ =0.003 and 0.004 respectively) were found to be less sensitive to water supply pressure as compared with Showerheads 1 and 2 ( $\phi_u^{'}$ = 0.008 and 0.11 respectively). In general, Showerheads 3 and 4 gave more even discharge patterns over the spray coverage and their uniformities were less sensitive to the water supply pressure.

**Table 6.1 Showerhead physical properties, spray attributes and aerosol generation rates**

| Parameter | Sample showerheads | | | |
|---|---|---|---|---|
| | **1** | **2** | **3**[a] | **4**[a] |
| *Showerhead* | | | | |
| Diameter, $D_s$ (m) | 0.080 | 0.045 | 0.115 | 0.085 |
| Number of 1/2/3 mm nozzles, $n_1/n_2/n_3$ | 48/19/10 | 48/9/0 | 59/9/0 | 53/15/0 |
| Nozzle area ratio, $\phi_A$ | 0.0334 | 0.0415 | 0.0072 | 0.0156 |
| Resistance factor, $k$ (kPa min$^2$ L$^{-2}$) | 1.82 | 1.90 | 16.50 | 3.36 |
| *Shower water spray measured at P=100 kPa (at 150 kPa)* | | | | |
| Flow rate, $Q_s$ (L s$^{-1}$) | 0.13 (0.16) | 0.12 (0.14) | 0.04 (0.05) | 0.10 (0.12) |
| Spray spread angle, $\theta_s$ (°) | 11 (11) | 2 (2) | 11 (11) | 9 (9) |
| Spray jet velocity, $v_s$ (m s$^{-1}$) | 0.77 (0.95) | 1.82 (2.12) | 0.56 (0.70) | 1.13 (1.35) |
| Momentum, $M_s$ (×10$^{-4}$ m$^4$ s$^{-2}$) | 1.01 (1.52) | 2.18 (2.97) | 0.24 (0.36) | 1.13 (1.62) |
| Uniformity, $\phi_u$ | 0.21 (0.62) | 5.95 (0.58) | 0.68 (0.52) | 0.33 (0.51) |
| Spray force, $F_s$ (N) | 0.75 (1.06) | 1.05 (1.32) | 0.34 (0.44) | 0.62 (0.98) |
| Aerosol mass generation rate, $\dot{m}_g$ (×10$^{-5}$ gs$^{-1}$) | 2.85 (3.92) | 3.03 (5.52) | 1.42 (3.03) | 2.14 (3.38) |

[a]WELS rated Grade 1 showerhead.




x-axis: Distance from showerhead $l_s$ (m); y-axis: Mass flux density $u_{s,l}$ (kg $s^{-1}$ $m^{-2}$)

**Figure 6.2 Showerhead water spray mass flux density**

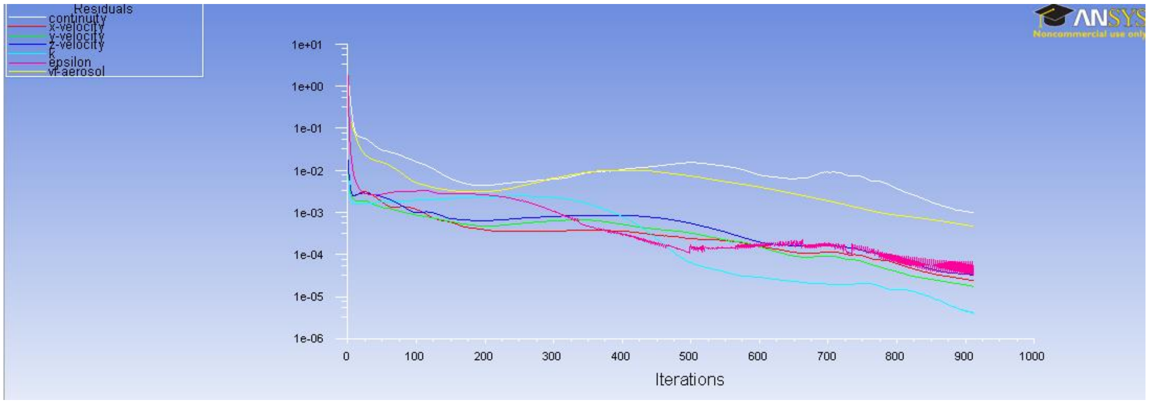
### 6.3 Results of chamber tests and CFD simulations

For the experiment shown in Figure 3.6, the collected salt mass on the dried filter paper sample for showerheads 1, 2, 3 and 4 under pressures 1 bar (1.5 bar) were 0.0016 g (0.0022 g), 0.0017 g (0.0031 g), 0.0008 g (0.0017 g) and 0.0012 g (0.0019 g) respectively. Based on Equation 3.35, the aerosol mass exhaust rate $\dot{m}_o$ in the chamber for showerheads 1, 2, 3 and 4 operations under pressure 1 bar (1.5 bar) were calculated as $7.41\times10^{-6}$ $gs^{-1}$ ($10.20\times10^{-6}$ $gs^{-1}$), $7.87\times10^{-6}$ $gs^{-1}$ ($14.40\times10^{-6}$ $gs^{-1}$), $3.70\times10^{-6}$ $gs^{-1}$ ($7.87\times10^{-6}$ $gs^{-1}$) and $5.56\times10^{-6}$ $gs^{-1}$ ($8.80\times10^{-6}$ $gs^{-1}$) respectively.

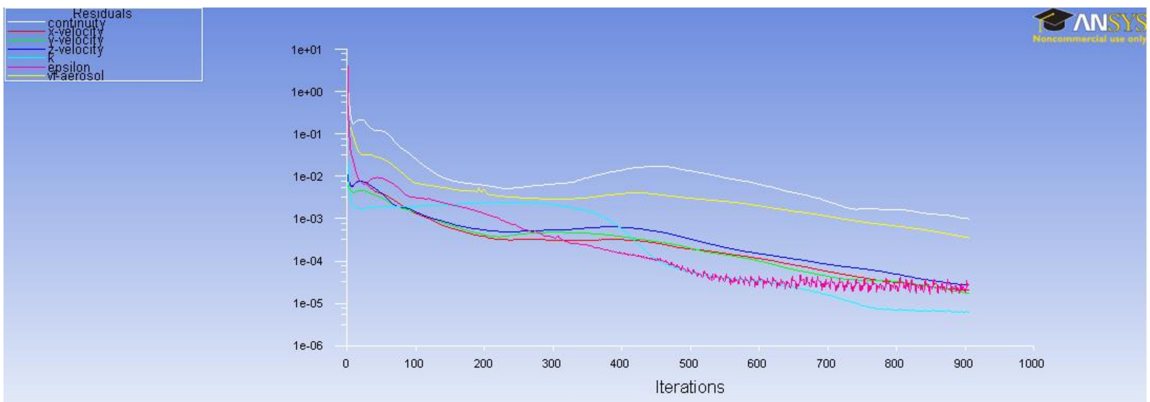
For CFD model validation, calculations at the four fan speeds namely 1000, 2000, 3000 and 4000 rpm were converged after about 1000 iterations with the residuals of continuity, velocity, k value, ε value, and volume fraction of aerosol phase, decreasing three orders of magnitude, as exhibited in Figure 6.3. The volume fractions of aerosol phase $\delta_{pr}$ at sampling point in the chamber were acquired, and corresponding aerosol concentrations $C_{pr}$ (particles $m^{-3}$) at the point were calculated using Equation 6.2, where $V_{pr}$ is an aerosol volume.

$$C_{pr} = \frac{\delta_{pr}}{V_{pr}} \tag{6.2}$$

(a)


Residuals
continuity
x-velocity
y-velocity
z-velocity
k
epsilon
vf-aerosol
ANSYS
Noncommercial use only
1e+01
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
0
100
200
300
400
500
600
700
800
900
1000
Iterations

(b)


Residuals
continuity
x-velocity
y-velocity
z-velocity
k
epsilon
vf-aerosol
ANSYS
Noncommercial use only
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1e+00
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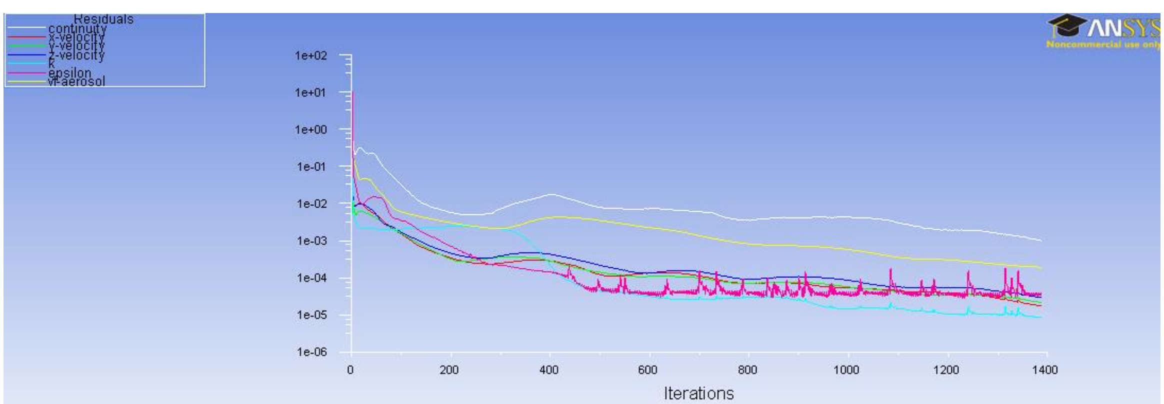
1e-02
1e-03
1e-04
1e-05
1e-06
0
100
200
300
400
500
600
700
800
900
1000
Iterations

(c)


Residuals
continuity
x-velocity
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z-velocity
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epsilon
vf-aerosol
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Noncommercial use only
1e+02
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1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
0
200
400
600
800
1000
1200
1400
Iterations

(d)

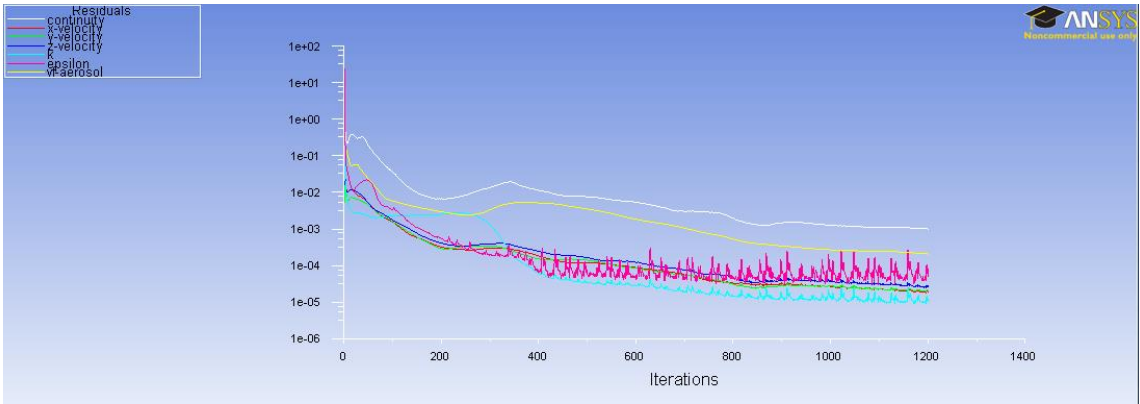



**Figure 6.3 Residuals of numerical calculation for validation: (a) Fan rotational velocity = 1000 rpm; (b) Fan rotational velocity = 2000 rpm; (c) Fan rotational velocity = 3000 rpm; (d) Fan rotational velocity = 4000 rpm**

For the case with fan speed 2000rpm, the simulated value of aerosol concentration at the sampling point was $1.89\times10^{7}$ particles $m^{-3}$, and that was very close to the value found in Carson's experiment ($1.97\times10^{7}$ particles $m^{-3}$) (Carson 1996).

Based on the setting in the CFD models that the aerosol motion had no effect on the air phase motion, and there was no slip velocity between air phase and aerosol particle phase, it can be seen that aerosol tracks were totally dependent on the air motion paths. The CFD models that govern the air-aerosol flow in chambers were validated. This also implies that, together with the aerosol tracking model (i.e. Lagrangian discrete phase model (DPM) in this study), the CFD models that govern the air-aerosol flow in chambers can be used directly for the aerosol tracking (deposition) study.

For the CFD simulations of aerosol generation in the test chamber, the numerical calculations stopped after about 1100 iterations with the residuals of continuity, velocity, k value, ε value and volume fraction of aerosol phase decreased three orders of magnitude, as shown in Figure 6.4. Even though there was vibration of residual curves during the calculation, which may be due to the mesh size and mesh quality, the vibration then disappeared after about 900 iterations. As the vibration of residual curves just happened in the middle of the calculation, it was considered that no effect was caused to the calculation convergence and results in this study. The calculation results showed that among the total number of tracked aerosols (i.e. $n_w+n_o$=12000), $n_w$=8933 aerosols were trapped on the chamber walls, corresponding to an aerosol deposition fraction on the chamber wall $\phi_w$=0.74. Double tracked aerosol number (i.e. $n_w+n_o$=24000) was tried, and same aerosol deposition fraction on the chamber walls was found (i.e. $\phi_w$=0.74). This implies that: (1) the 12000 tracers can represent the full aerosol behavior range in this study; and (2) aerosol deposition fraction on the chamber walls is independent of aerosol generation rate. The aerosol deposition is related to the specific aerosol properties, ventilation conditions and chamber dimensions. Aerosol deposition fraction $\phi_w$=0.74 is for the case in this study.

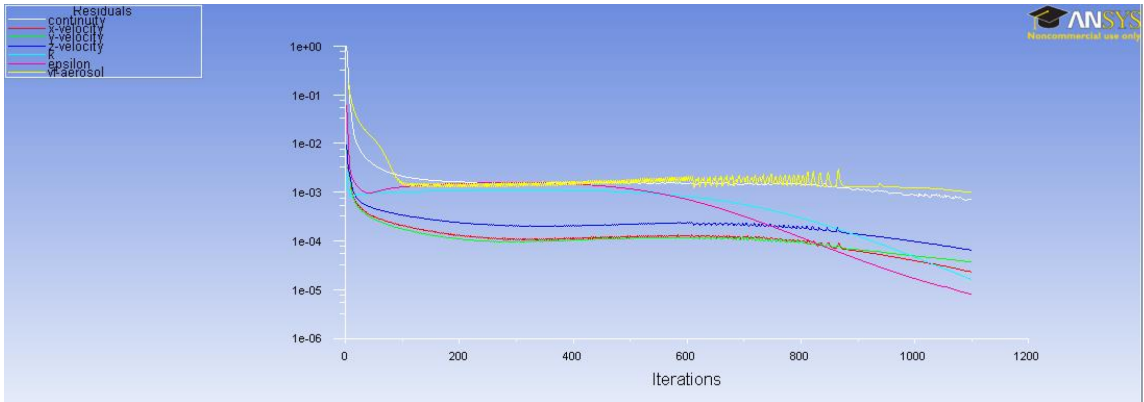



**Figure 6.4 Residuals of numerical calculation**

### 6.4 Aerosol generation rate and correlations with showerhead attributes

Using the experimental aerosol mass exhaust rate $\dot{m}_o$ and simulated aerosol deposition fraction $\phi_w$, the showerhead aerosol mass generation rates $\dot{m}_g$ were calculated by Equation 3.43, and summarized in Table 6.1.

Average diameter (=4.25 μm) of aerosols generated from showerheads was determined according to the studies by Bollin et al. (1985) and Zhou et al. (2007), then corresponding volume of an aerosol $V_{pr}$ (=40.17 μm$^3$) was calculated. The aerosol particle generation rates $\dot{n}_g$ (particles s$^{-1}$) can be given by Equation 6.3. Results show that aerosol particle generation rate for the four sample showerheads ranged from $0.35\times10^6$ particles s$^{-1}$ to $1.35\times10^6$ particles s$^{-1}$. Compared with the previous experimental results for taps (=$0.234\times10^6$ particles s$^{-1}$) reported by Carson (1996), the results validate the assumption that showerheads generate more aerosols than water taps as showerheads have more holes on faceplate.

$$\dot{n}_g = \frac{10^{15}\dot{m}_g}{\rho_t V_{pr}} \tag{6.3}$$

Table 6.1 shows that aerosol mass generation rate increased with water supply pressure at showerhead. The ratios of aerosol mass generation rate to water supply pressure for the four sample showerheads were plotted in Figure 6.5, in which a reference line indicates perfectly linear increase of aerosol generation rate with water supply pressure at showerhead. By defining acceptable error range, linear increase of aerosol generation rate with water supply pressure at showerhead can be concluded from Figure 6.5.

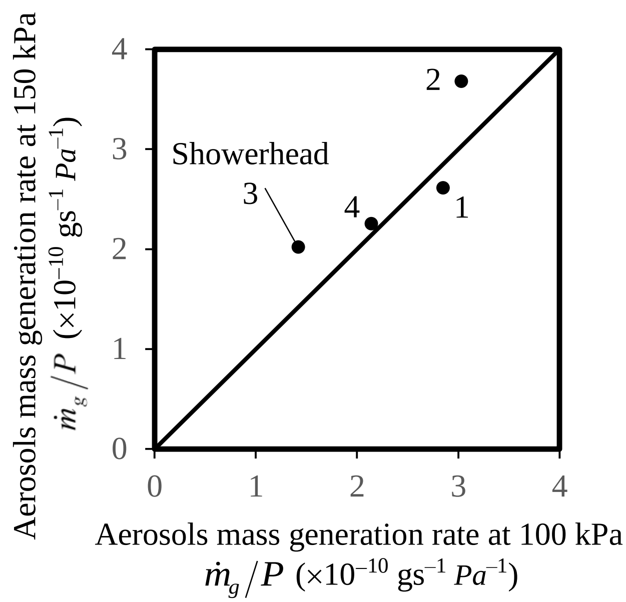



**Figure 6.5 Ratio of aerosol mass generation rate to water supply pressure at showerhead**

Figures 6.6(a) to 6.6(g) illustrate the ratio of aerosol mass generation rate to water supply pressure $\dot{m}_g/P$ (×10$^{-10}$ gs$^{-1}$ $Pa^{-1}$) against the nozzle area ratio $\phi_A$, showerhead resistance factor $k$ (kPa min$^2$ L$^{-2}$), water supply flow rate $Q_s$ (L s$^{-1}$), spray jet velocity $v_s$ (m s$^{-1}$), spray jet momentum $M_s$ (m$^4$ s$^{-2}$), uniformity $\phi_u$ and spray jet force $F_s$ (N) respectively. All parameters except uniformity shows a significant correlation with the aerosol mass generation rate ($p \leq 0.05$, $t$-test). As shown in Figures 6.6(a) to (e), and Figure 6.6(g) the aerosol mass generation rate decreases with the showerhead resistance factor but increases with the water supply pressure, nozzle area ratio, flow rate, spray jet velocity, momentum and force. While water supply pressure, nozzle area ratio, flow rate, spray jet velocity and momentum are all related to showerhead itself, spray jet force is exerted by the spray-surface interaction. The spray jet force is an indicator of the splashing effect caused by water spray jet impaction on a surface; a greater force produces a greater splashing effect and thus more aerosols.

The relationship between aerosol mass generation rate and showerhead attributes can be expressed by,

$$\frac{\dot{m}_g}{P} \sim \left(\phi_A, k, Q_s, v_s, M_s, F_s\right);$$

$$M_s \sim \left(Q_s, v_s\right)\ ;$$

$$k \sim \left(P, Q_s\right);$$

$$F_s \sim \left(Q_s, v_s\right) \tag{6.4}$$

It can be rewritten as,

$$\frac{\dot{m}_g}{P} \sim \left(\phi_A, M_s\right) \tag{6.5}$$

Corresponding equations for the trend-lines in Figure 6.4(a) and Figure 6.4(e) were given as following,

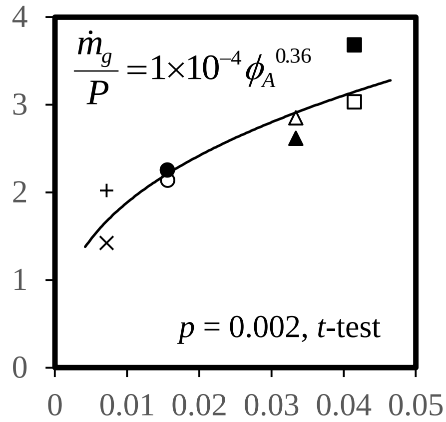
$$\frac{\dot{m}_g}{P} = 1 \times 10^{-4} \phi_A^{0.36} \ ;$$

$$\frac{\dot{m}_g}{P} = 0.004 M_s^{0.3} \tag{6.6}$$

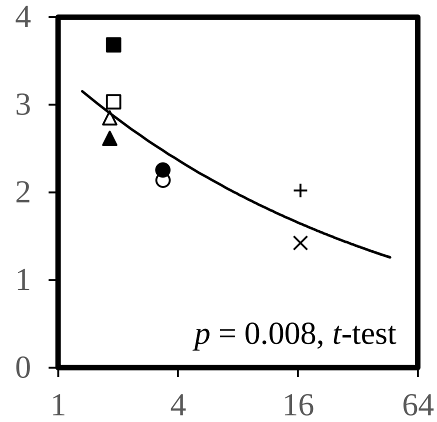
As Equation 6.6 shows that $\dot{m}_g / P \sim \phi_A^{0.36}$ and $\dot{m}_g / P \sim M_s^{0.3}$, the aerosol generation rate $\dot{m}_g / P$ against $M_s^{0.3} \phi_A^{0.36}$ was plotted in Figure 6.7 for analysis. Figure 6.7 gives the expression of aerosol mass generation rates $\dot{m}_g$ ($gs^{-1}$) by water supply pressure, spray jet momentum and nozzle area ratio, with $p$=0.001 ($t$-test).

$$\dot{m}_g = 0.00022 P M_s^{0.16} \phi_A^{0.19} \tag{6.7}$$

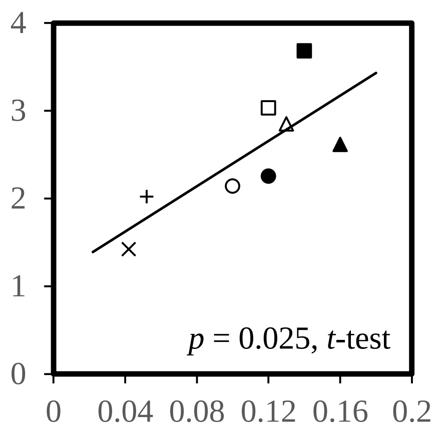
As the results are from the test range, which delinked from the graded showerheads. Therefore, Equation (6.7) can be the referenced guidance for future showerhead design to limit the aerosol generation rate.



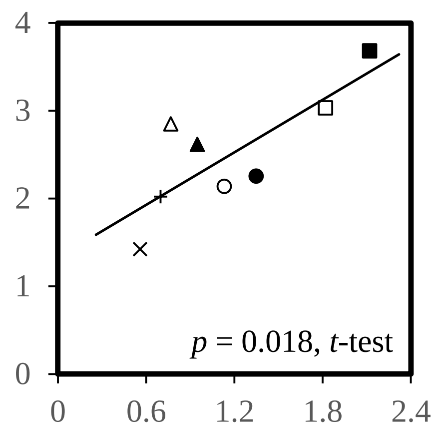

(a) Nozzle area ratio $\phi_A$



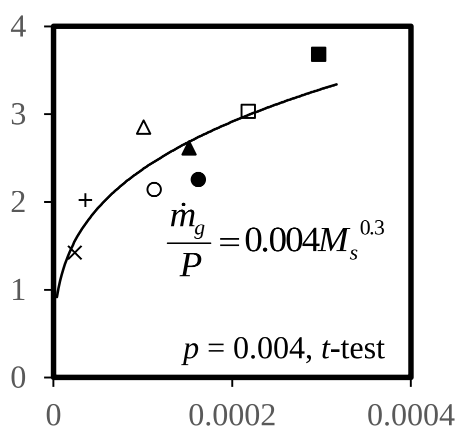

(b) Resistance factor $k$ (kPa min$^2$ L$^{-2}$)



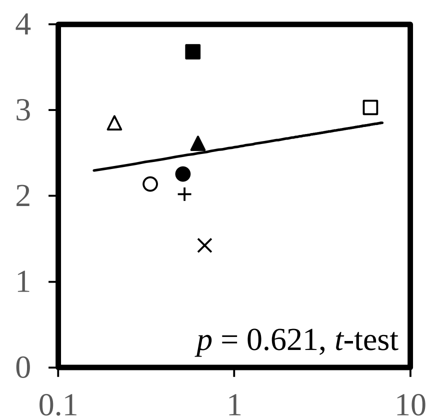

(c) Flow rate $Q_s$ (L s$^{-1}$)



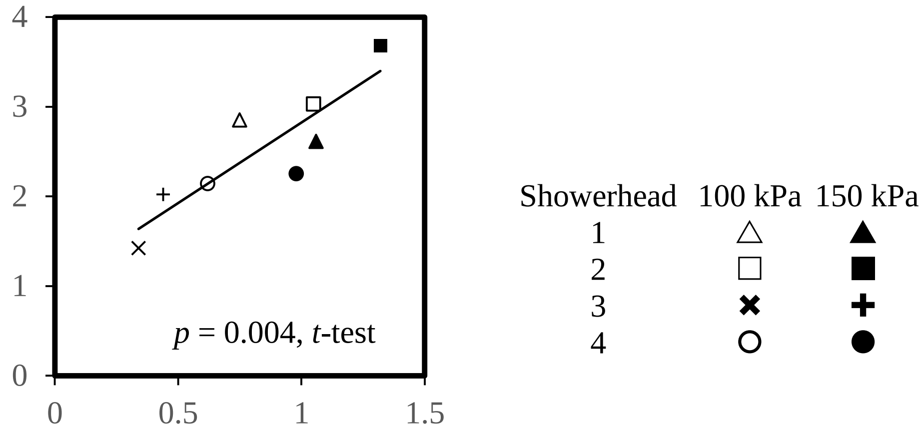

(d) Jet velocity $v_s$ (m s$^{-1}$)




(e) Momentum $M_s$ (m$^4$ s$^{-2}$)



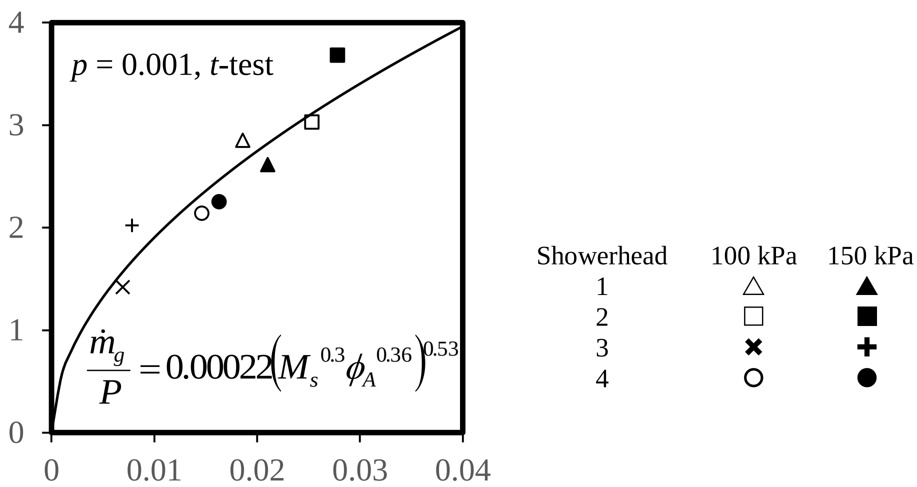

(f) Uniformity $\phi_u$




(g) Spray force $F_s$ (N)

y-axis: Aerosols mass generation rate $\dot{m}_g / P$ ($\times 10^{-10}$ gs$^{-1}$ $Pa^{-1}$)

**Figure 6.6 Correlations for aerosol mass generation rate**




x-axis: $M_s^{0.3}\phi_A^{0.36}$; y-axis: Aerosols mass generation rate $\dot{m}_g / P$ ($\times 10^{-10}$ gs$^{-1}$ $Pa^{-1}$)

**Figure 6.7 Aerosol mass generation rate as a function of $M_s^{0.3}\phi_A^{0.36}$**

### 6.5 Effect of low flow showerhead on aerosol generation rate

Table 6.1 shows that when all sample showerheads were operating at the same pressure, the aerosol generation rates of the low flow showerheads, i.e. Showerheads 3 and 4, were less than those of Showerheads 1 and 2. Our previous study (Chan et al. 2016) revealed that the optimum pressure of low flow showerheads was larger than that of conventional showerheads, which contributes to the aerosol generation; however, the aerosol generation rate of a low flow showerhead can still be controlled by the adjustment of momentum $M_s$ and nozzle area ratio $\phi_A$ as demonstrated by Equation 6.7.

As shown in Table 6.1, low flow Showerheads 3 and 4 have less large holes on the showerhead faceplate compared with Showerhead 1 and 2. It can be seen that the two sample low flow showerheads in this study were achieved by reducing average hole size. There is also another type of low flow showerhead which induces air into showerhead (Toyosada et al. 2013), that is not included in this study as the time limited. This type of low flow showerhead mixes air with water to enlarge water droplet, corresponding a fine mist may be caused, and further aerosol generation rate may be increased. Besides the parameters shown in Equation 6.7 (i.e. water supply pressure at showerhead $P$, spray jet momentum $M_s$ and nozzle area ratio $\phi_A$), for future studies, parameters of induced air flow rate, air volume, and air pressure should be considered when investigating the aerosol generation rate of low flow showerheads of air-water mixing type.

### 6.6 Summary

Experimental and CFD simulation results of aerosol generation of showerheads in the chamber were presented. It showed that aerosol mass generation rates of the four sample showerheads ranged from 1.42 to 5.52 $gs^{-1}$. Meanwhile, aerosol particle generation rates of the four sample showerheads were calculated, and that was $0.35 \times 10^6$ particles $s^{-1}$ - $1.35 \times 10^6$ particles $s^{-1}$. It showed that aerosol mass generation rate decreased with the showerhead resistance factor but increased with the water supply pressure, nozzle area ratio, flow rate, spray jet velocity, momentum and force. No significant correlation was found between aerosol mass generation rate and water spray uniformity ($p$=0.621, $t$-test). In order to quantify the correlations between aerosol generation rate and showerhead attributes, expression of aerosol mass generation rate by water supply pressure at showerhead, nozzle area ratio and spray jet momentum was given. This expression can be used as a referenced guidance for the future showerhead design to limit the aerosol generation rate.

It was revealed that the two sample low flow showerheads have smaller holes on showerhead faceplate compared with that of other two sample conventional showerheads. In other words, the two sample water efficient showerheads in this study were achieved by reducing the average hole size. Besides, the water distribution patterns of the two sample low flow showerheads were less sensitive to water supply pressure as compared with that of the two sample conventional showerheads. Under the same operation pressure, aerosol generation rates of the two sample low flow showerheads were found less than that of other two sample conventional showerheads. For the situation of usually higher operation pressure of low flow showerheads, the aerosol generation rate still can be limited by adjustment of nozzle area ratio and spray jet momentum reference to the proposed expression of aerosol generation rate by showerhead attributes. For the type of low flow showerheads with air-water mixing, the aerosol generation rate should be analyzed specifically in future studies.

# Chapter 7

# Conclusion

## 7.1 Summary of the study

In order to promote the water efficient appliances, water efficiency labelling schemes on water consuming appliances have been proposed and implemented in different countries or regions, including in Hong Kong, for several years. The schemes help consumers select water efficient plumbing fixtures and water consuming appliances. In this thesis, a comprehensive impact evaluation of low flow showerheads for bathing of Hong Kong was performed. The impact of low flow showerheads for bathing was evaluated from three aspects, namely shower water consumption, and associated energy use and corresponding $CO_2$ emissions; design flow rate of water supply system inside buildings; and aerosol generation rate of showerhead. Different methods were chosen for solving the questions identified in these three aspects, including questionnaire survey, field measurement, Monte Carlo simulation, experimental study and computational fluid dynamics (CFD) simulation.

Monte Carlo simulations of shower water consumption (with input parameter values from field survey) revealed that with the existing showerheads, per capita annual shower water consumption was 24.3 $m^3\ ps^{-1}\ yr^{-1}$, while energy use for heating hot shower water was 1.66 GJ $ps^{-1}\ yr^{-1}$, and $CO_2$ emissions was 384 kg-$CO_2\ ps^{-1}\ yr^{-1}$. Comparatively, the per capita annual shower water consumption was 15.4-21.0 $m^3$ $ps^{-1}$ $yr^{-1}$ with low flow showerheads, and energy use for heating hot shower water was 1.24-1.50 GJ $ps^{-1}$ $yr^{-1}$, and $CO_2$ emissions was 283-345 kg-$CO_2$ $ps^{-1}$ $yr^{-1}$. For the limiting case, the theoretically maximum benefits of  reducing water consumption by 37%, energy use by 25% and $CO_2$ emissions by 26% can be achieved with full installation of low flow showerheads, i.e. WELS rated Grade 1 showerheads ($\leq$ 9 L $min^{-1}$).

Design flow rate of water supply system in two cases (Case A: all appliances, including showerheads, wash basins, kitchen sinks and washing machines, were conventional ones; Case B: showerheads are low flow ones, while other types of appliances were conventional ones) were estimated by another Monte Carlo simulations. It revealed that the inflow rate in up-feed pipe of water supply system in Case A were 16.4-17.9 $Ls^{-1}$, while in Case B with low flow showerhead demands, the inflow rates were 13.8-15.1 $Ls^{-1}$. Reduced design flow rate (reduction of 15%) was shown for Case B when compared with that for Case A, which was due to the water consumption reduction (reduction of 11%) by full installation of low flow showerheads. The energy efficiency of the water supply system with the reduced design flow rate was evaluated (assuming with an unaltered pipe size), and it showed a slight improvement of system energy efficiency, i.e. system energy efficiency increased from 0.266 to 0.270 corresponding to the design flow rate decreased from 17.9 $Ls^{-1}$ to 15.1 $Ls^{-1}$. From the engineering judgement, it seems unnecessary to redesign the inflow rate of water supply system when with low flow showerheads for bathing. For the situation with installation of all types of water efficient appliances, the redesign of inflow rate should be justified further.

Aerosol generation rates of four sample showerheads, including two low flow showerheads and two conventional showerheads, were experimentally studied in a glass test chamber, assisted with computational fluid dynamics (CFD) simulations. Aerosol mass generation rates of 1.42 - $5.52\times10^{-1}$ $gs^{-1}$ were found, and aerosol particle generation rates were $0.35\times10^{6}$ - $1.35\times10^{6}$ particles $s^{-1}$. It was revealed that aerosol generation rate was correlated with multi-parameters: it decreased with the showerhead resistance factor but increased with the water supply pressure, nozzle area ratio, flow rate, spray jet velocity, momentum and force. An expression of aerosol generation rate by limited parameters, i.e. water supply pressure at showerhead, nozzle area ratio and spray jet momentum, was given. Under same operating pressures, aerosol generation rates of two sample low flow showerheads were found lower than that of other two sample conventional showerheads. For the situation of usually higher operation pressure of low flow showerheads, which contributes to the aerosol generation, the aerosol generation rate of low flow showerheads still can be limited by adjustment of nozzle area ratio and spray jet momentum reference to the proposed expression of aerosol generation rate.

## 7.2 Implications and recommended directions for future research

This thesis confirms that installation of low flow showerheads is an effective way for the demand side water conservation. In order to achieve the expected water saving goal, rebound effect while using water efficient appliances should be concerned. As identified by the thesis that users can accurately sense the water temperature and water use time by their subjective judgement, further water conservation education on active changes of water use habit is needed. The quantification of the shower water consumption, and associated energy use and corresponding $CO_2$ emissions in this thesis provides a reference for the establishment of carbon credit trade for residential water use section in the future.

The issue about the influence of low flow showerheads for bathing on water supply system design was identified and discussed in this thesis. The justification of the redesign of inflow rate after installation of low flow showerheads provides useful benchmark references for not only water supply system designs but also water demand management programmes in buildings. For the situation that all types of appliances connected to the water supply systems are water efficient ones, further justification of the redesign of the inflow rate is needed.

The health safety problem, i.e. aerosol generation rate, related to the low flow showerheads was handled in this thesis. The proposed aerosol generation expression gives guidelines for the future low flow showerhead design to limit the aerosol generation rate, which is helpful for manufacturers as well as policymakers. Moreover, as shower spray is composed of water jets, investigation of aerosol generation rate of water jets is suggested for better understanding of showerhead aerosol generation.

### 7.3 Limitations of the study

The accuracy of the Monte Carlo simulations in the thesis was highly dependent on the input parameter values which were collected by field surveys. Limited survey studies showed that shower duration did not change after replacement of conventional showerheads with low flow ones, and the conclusion was adopted for the simulation of water consumption, associated energy use and corresponding $CO_2$ emissions with low flow showerheads. As the data about shower behaviors with low flow showerheads is limited, the Monte Carlo simulation results may be compromised.

For the experimental study of aerosol generation rate for showerheads, salt was dissolved in the distilled water to simulate the existence of Legionella bacteria. Researchers have different opinions about the influence of dissolved salt on the aerosol generation rates nowadays. The use of salt water may have some influence on the results. For the CFD simulation of aerosol generation in the chamber, two models were applied, i.e. Euler-Euler multiphase model for air and aerosol flow, and Lagrangian discrete phase model (DPM) for aerosol tracking. As no slip velocity between air phase and aerosol particle phase was assumed, which means that the aerosol tracks were totally dependent on the air motion paths, only Euler-Euler multiphase model was validated in the study. Theoretically, it is convincible to use the Lagrangian discrete phase model directly without validation, future validations can also be done to confirm the results.

# Appendices

## Interview questions

*Part A: Details of the washroom facilities surveyed*

Washroom details, including number of users, showerhead operation modes and hole configurations, showerhead WELS rated or not, hot water energy source and willingness of users to upgrade an existing showerhead to improve water efficiency, were obtained.

*Part B: User feedback on showerheads*

1. Do you take showers using the showerhead described in the survey?
2. How many showers do you take every day?
3. How long do you spend in each shower?
4. Do you keep your showerhead running in a shower?
5. How long do you run your showerhead in each shower?
6. Do you fill up your bathtub when you bathe?
7. Do you fill up your bathtub while using the showerhead?
8. How frequent do you take a cold (hot) shower? You may give an estimate in days.
9. How many days have you bathed in cold water in the past year?
10. How frequent do you shampoo? You may give an estimate in days. How long is your shampooing routine?

11. Are you satisfied with your existing showerhead?

12. Please estimate your favorite shower water temperature.

13. Please describe your favorable feelings about the amount of shower water.

14. Please describe your favorable feelings about the pressure of shower water.

*Part C: User feedback after using the Water Efficiency Labelling Scheme (WELS) Grade 2 showerhead*

1. Are you satisfied with the performance of the WELS rated showerhead?
2. Which showerhead do you prefer, the original or the WELS?
3. Will you keep using the WELS rated showerhead?
4. Are you satisfied with the water pressure?
5. Are you satisfied with the water amount?
6. How would you prioritize the following: bathing comfort and water savings?
7. Please estimate your favorite shower water temperature.
8. Did you take longer showers?
9. Did you shampoo more often?

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