

Thermodynamic analysis on an instantaneous water heating system of shower wastewater source heat pump

Yuguo Wu, Yake Jiang, Bo Gao, Zhigang Liu and Jing Liu

ABSTRACT

Water reuse and desalination systems are energy intensive processes, and their increasing use is leading energy consumption within water systems to be an increasingly important issue. Shower wastewater contains large amounts of heat, so there is an opportunity to recover energy from shower water to offset energy consumption elsewhere in water systems. This paper found ways to increase the output of hot water and lower the energy consumption by establishing a thermodynamic model of an instantaneous wastewater source heat pump. The system proved to be very effective, the heating *COP* (coefficient of performance) can reach 3.3 even in the winter. Under the conditions of limited heat transfer area, reducing the suction pressure of a compressor is a more feasible way to increase the hot water output to meet the needs of users rather than increasing the discharge pressure. Besides, increasing the heat transfer area of the evaporator is a more effective option. When the heat transfer area of evaporator varies from 0.5 to 1.0 square meters, a notable change is that the heating *COP* increases from 3.283 to 3.936. The heating *COP* in a system with a recuperator can reach 5.672, almost double that compared to the original systems.

Key words | heat pump, recycle waste heat, shower, thermodynamic analysis

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INTRODUCTION

Energy efficiency is a topic rarely talked about in the field of water reuse and desalination, but it is of great importance. The California Energy Commission and the WaterReuse Research Foundation had joined forces to support five individual projects which address energy efficiency in both water reuse and desalination (Pinzón 2013). In a sense, water is also a source of energy; water reuse processes should take into account the energy reuse, e.g. sewage and treated water can be a heat source in urban areas due to large heat capacity, thus recovery and reuse of its energy is one of the most desirable plans for the sewerage system. Energy saving is the eternal theme of the heating water

technology, the breakdown of energy consumption in residences showed that 20% of the energy was for the production of hot water. The proportion of hygienic hot water's energy consumption in the building energy consumption is becoming larger and larger, and in commercial buildings in the cities has reached 10–40%, and 20–30% in civil constructions (Xiao *et al.* 2014), of which a large portion was used for bathing or showering. A truly efficient domestic hot water system can optimize energy savings. Wong *et al.* (2010) investigated the potential for shower water heat recovery from bathrooms equipped with instantaneous water heaters in high-rise residential buildings of Hong Kong, and indicated that annual energy savings of 4–15% from shower water heat could be achieved through a 1.5 m long single-pass counter-flow heat exchanger for a drainage pipe of 50 mm diameter. Guo *et al.*

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(2014) reported that more than 50% of shower waste water heat can be recycled by a high-performance heat recovery device, and the shower waste was assumed to have a promising prospect in application. McNabola *et al.* (2013) presented the development and analysis of a horizontal drain water heat recovery system for domestic showers, and the results demonstrate that the system has the potential to reduce energy usage and CO₂ emissions significantly. However, the systems mentioned above were all based on conventional water heaters, such as electric heater and gas heater, which have the disadvantage of high energy consumption.

Development and application of a heat pump is one method of water heater, and the recycling of waste heat produced during a shower is the most effective way to improve the energy efficiency of the heat pump water heater. Chen *et al.* (2013) designed a heat pump water heater for showering, which was assisted by waste water heat recovery and could supply hot water in a few minutes of waiting, just like an instantaneous water heater. When the condensing and evaporating temperatures are optimized at 51.50 and 11.68 °C, respectively, the optimal coefficient of performance (COP) of the whole system reaches 4.97, which is much higher than that of the conventional air source heat pump water heater. Dong *et al.* (2015) proposed a novel heat pump water heater recycling shower drain water and the experimental results showed that approximately 70% of energy could be saved using this novel heat pump water heater, compared with a traditional electric water heater. Wang (2011) inferred that the heat pump water heater system had advantages such as quick starting, compact structure, no need of hot water tank, stable operation and energy saving, etc. It could be used to supply hot water above 40 °C for showering or heating, ventilation and air conditioning. Wallin & Claesson (2014) analyzed the influence of different drain water flow rate profiles on the performance of a heat pump base inline heat recovery system, and the results showed that this type of heat recovery system was able to recycle a large portion of heat in the drain water if appropriately sized.

From a practical point of view, sanitation and ease of cleaning must be taken into consideration in the household shower wastewater heat recovery system, so those solutions with a wastewater collection tank will not be welcome, and

a single layer plane type heat recuperator placed underfoot seems to be necessary. However, the heat transfer area is extremely limited, which is a bottleneck for the development of a wastewater source heat pump water heater. In a summary of the current research, Chen *et al.* (2013) concluded that the most efficient and convenient solution to instantly recover the shower wastewater heat was by using the instantaneous heat pump water heater. However, it is still doubtful whether the instantaneous heat pump water heating system can work well using the shower wastewater as the only heat source, especially when the tap water temperature is much lower and the heat transfer area is restricted. To this end, a thermodynamic model of an instantaneous wastewater source heat pump water heating and showering system was established, simulations and analysis were carried out to investigate the energy efficiency and hot water yield under different operating conditions.

MODELLING

The study was conducted by modelling the water heater system and analyzing the thermodynamic heat and mass balance of the wastewater source heat pump cycle using EBSILON[®] Professional software. EBSILON[®] Professional is a commercial software that simulates thermodynamic cycle processes and is used for engineering, designing, and optimizing plants (Prosin *et al.* 2015). Because of the broad flexibility of the system and the universality of the approach to solutions, it is possible to simulate virtually any thermodynamic cycle process. The topological structure of the wastewater heat source heat pump system model is illustrated in Figure 1, including some components to be used in the derived models, which are shown in the dashed box.

In the model, there are some assumptions and settings that need to be specified. The evaporator (1) was modeled by Component 70 (evaporator with steam drum), some user input values were input not by default, FSPEC (Pinch point method) = 30: Forced circulation, heat transfer area (nominal) AN given in design, AN (heat transfer area (nominal)) = 0.5 m², and K (heat transfer coefficient) resulted in 500 W/m² K. The condenser (4) was modeled by Component 7, FSPEC (specification (for design)) = 2: T2 external specified, T2 denoted shower outlet temperature

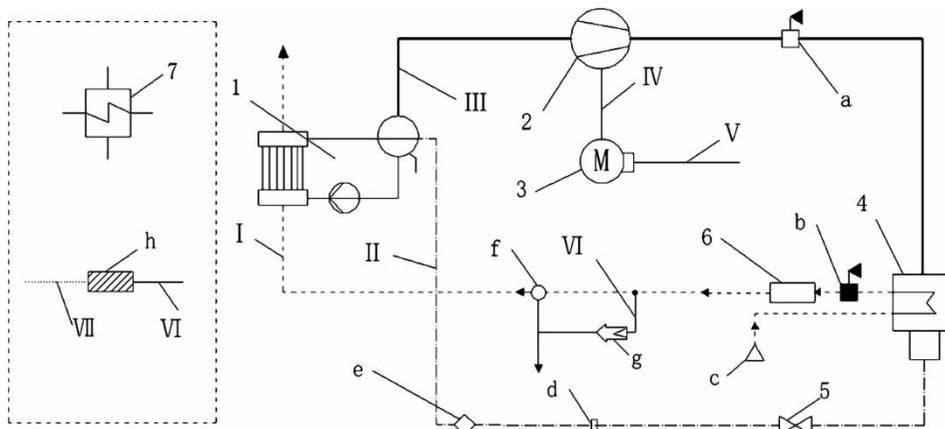


Figure 1 | The topological structure of the wastewater heat source heat pump system model. 1: Evaporator; 2: compressor; 3: motor; 4: condenser; 5: throttle; 6: showering heat loss; 7: recuperator; I: water; II: liquid refrigerant; III: gaseous refrigerant; IV: shaft; V: electric (logic); VI: mass flow rate (logic); VII: actual value (logic); a: pressure; b: temperature; c: boundary value; d: separator (logic); e: type of medium; f: splitter; g: mass flow rate value transmitter; h: controller.

and was set to 45 °C by measured value input component (b). The showering heat loss (6) was assumed to be a temperature drop of 7 K, in other words, the temperature of shower wastewater was set to 38 °C. The mass flow rate value transmitter (g) allocated 10% of shower waste water to discharge into the sewer directly, that means 90% of the shower wastewater would pass through the splitter (f) into the evaporator for heat exchange. R134a was selected as the refrigerant, and its properties were calculated by REFPROP.

In order to verify the validity of the model, the experimental data reported by Kim *et al.* (1994) were taken as a comparison. In order to match the experimental conditions, a few minor changes were made, a superheater was inserted into the system. Without the superheater, the model in Figure 1 would produce some errors, but these are small enough to be ignored. In addition, according to the performance of the fixed speed compressor used in the experiment, the isentropic efficiency of the compressor model was adjusted to 0.8295 from 0.8, and the electrical efficiency of the motor model was adjusted to 0.87 from 0.85, thus the calculated data met well with the suction pressure, the discharge pressure, the suction temperature, the discharge temperature of the compressor and the compressor power. The modified model and the calculated data are illustrated in Figure 2 and the comparison results are listed in Table 1. All data are in good agreement; the maximum absolute relative deviation is

less than 1%, indicating that the model and the software are very reliable.

RESULTS AND DISCUSSION

Based on the model shown in Figure 1, simulations were carried out under different feed water temperature conditions, ranging from 5 to 30 °C, when the suction pressure of the compressor was kept to 2.5 bar and the discharge pressure was kept to 13.2 bar. As mentioned above, the heat exchange area of the evaporator was limited to 0.5 m², assuming the heat transfer coefficient was 500 W/m² K and no vapor was superheated. Results are curved in Figure 3, where it is revealed that the compressor power (P_{com}/kW) and volume flow rate of outlet water (M/L/min) increase with the increasing temperature of feed water ($t/°C$), but the heating COP maintains a constant value of 3.3. The reason is that the net heat transfer of the evaporator is only related to the volume flow rate of wastewater in the above specified conditions, the latter increases with the increase of the outlet water volume flow rate due to the increase of the feed water temperature, and the compressor power increases with the volume flow rate of the refrigerant R-134a due to the increase of the heating load of evaporator, so that the heating load of the condenser also increases. It is also found that the output of hot water is less than 4 L/min when the feed water temperature is low, e.g. 5 or 10 °C, although the COP is not low,

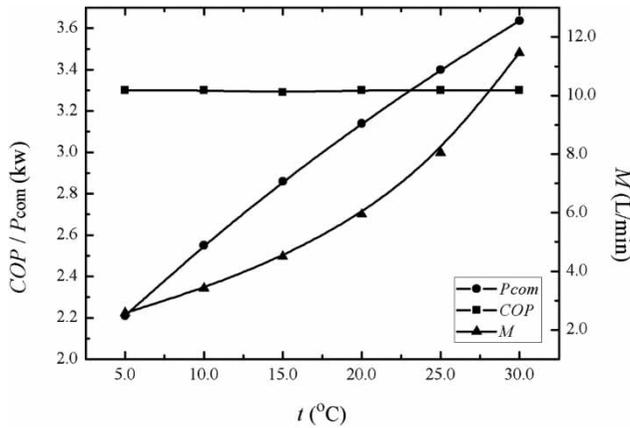


Figure 3 | The performance of the shower wastewater source heat pump system under different feed water temperature conditions.

which means it is difficult to meet the needs of shower water supply in winter. Therefore, it is necessary to find ways to increase the output of hot water if the instantaneous wastewater source heat pump water heating and showering system becomes a commodity in the future. Otherwise, it is also necessary to find ways to lower the energy consumption when the output of hot water is enough.

Reducing the suction pressure of the compressor is a feasible way to increase the hot water output, but the compressor power will be increased. Conversely, increasing the suction pressure of the compressor can reduce the hot water output and the compression power. Simulations were carried out under different suction pressures of compressor conditions, when the discharge pressure of the compressor was kept to 13.2 bar, and the feed water

temperature was 10, 15 and 20 °C, respectively. Results are listed in Table 2; the partial derivatives of COP and volume flow rate of output water (*M*) to the suction pressure of compressor (*p_e*) were calculated. It was found that the partial derivatives of COP to *p_e* are approximated to 0.7–0.8 at all feed water temperatures. It was also found that the partial derivatives of *M* to *p_e* are approximated to –2.0 to –2.6, which means that the volume flow rate of output water is very sensitive to the suction pressure of the compressor. This phenomenon can be explained by the phase diagram of R134a. Known from the saturated vapor pressure curve of R134a, in low pressure regions a small pressure drop can lead to a significant decline in saturation temperature, so lower suction pressure of the compressor significantly enhances the heat transfer of the evaporator due to larger mean logarithmic temperature differences.

Increasing the discharge pressure of the compressor is also an alternative way to increase the hot water output. Simulations were carried out under different discharge pressures of compressor conditions, when the suction pressure of the compressor was kept to 2.5 bar, and the feed water temperature was 10 and 15 °C, respectively. Results are listed in Table 3; the partial derivatives of COP and volume flow rate of output water to the discharge pressure of compressor (*p_c*) were calculated. It was found that the partial derivatives of COP to *p_c* are much smaller than that of COP to *p_e*, which means that increasing the discharge pressure of the compressor has little effect on the energy efficiency. Similarly, the partial derivatives of *M* to *p_c* are much smaller than that of *M* to *p_e*, so it is not a

Table 2 | Simulations under different suction pressures of compressor conditions

<i>t</i> (°C)	<i>p_e</i> (bar)	<i>t_e</i> (°C)	<i>t_c</i> (°C)	<i>P</i> (kw)	<i>M</i> (L/min)	<i>COP</i>	$\partial COP / \partial p_e$	$\partial M / \partial p_e$
10	2.0	–10.076	65.700	3.832	4.62	2.94	0.684	–2.400
	2.2	–7.638	64.767	3.263	4.14	3.08	0.710	–2.400
	2.5	–4.284	63.551	3.553	3.42	3.30	0.750	–2.400
15	2.5	–4.284	63.551	2.858	4.50	3.29	0.743	–2.060
	2.7	–2.217	62.837	2.460	4.08	3.44	0.757	–2.140
	3.0	0.672	61.881	1.951	3.42	3.67	0.777	–2.260
20	2.5	–4.284	63.551	3.135	5.94	3.30	0.712	–2.643
	2.7	–2.217	62.837	2.734	5.40	3.44	0.732	–2.515
	3.0	0.672	61.881	2.223	4.68	3.67	0.761	–2.323
	3.2	2.477	61.308	1.931	4.26	3.82	0.781	–2.195
	3.3	3.347	61.038	1.797	4.02	3.90	0.791	–2.131
	3.5	5.028	60.527	1.551	3.60	4.06	0.811	–2.003

Table 3 | Simulations under different discharge pressures of compressor conditions

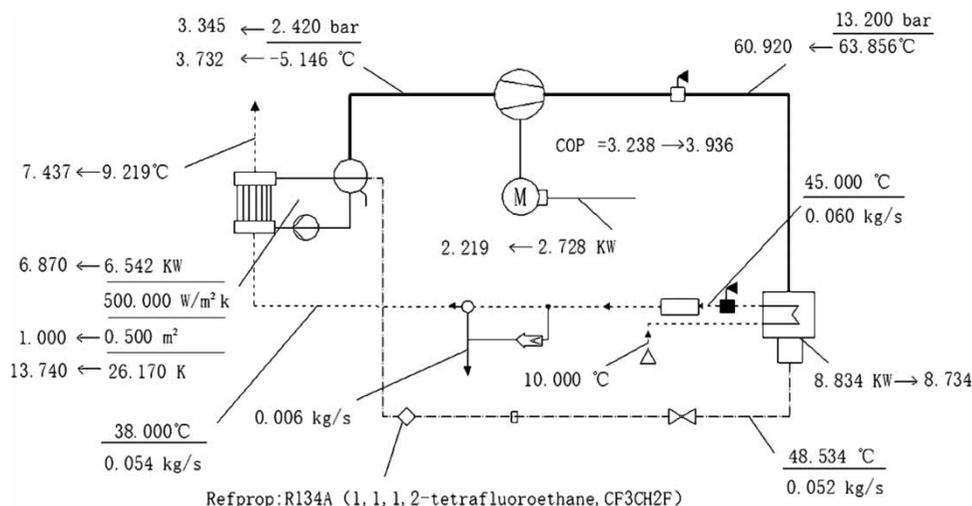
t (°C)	p_c (bar)	t_e (°C)	t_c (°C)	P (kW)	M (L/min)	COP	$\partial COP/\partial p_c$	$\partial M/\partial p_c$
10	13.2	-4.284	63.551	2.553	3.420	3.30	-0.200	0.210
	14.2	-4.284	66.911	2.818	3.600	3.11	-0.180	0.150
	15.2	-4.284	70.087	3.092	3.720	2.94	-0.160	0.090
15	11.0	-4.284	55.355	2.268	4.140	3.84	-0.295	0.182
	11.5	-4.284	57.329	2.399	4.260	3.70	-0.274	0.170
	12.0	-4.284	59.233	2.532	4.320	3.57	-0.253	0.158
	12.5	-4.284	61.073	2.667	4.380	3.45	-0.232	0.147
	13.2	-4.284	63.551	2.858	4.500	3.29	-0.202	0.130

good choice to reduce the volume flow rate of output water by increasing the discharge pressure of the compressor.

In fact, increasing the heat transfer area of the evaporator is a more effective way to improve the hot water output and the energy efficiency. Simulations were carried out under different heat transfer areas of evaporator conditions, when the discharge pressure of the compressor was kept to 13.2 bar, the feed water temperature was 10 °C and the mass flow rate of output water was kept to 0.060 kg/s. Results are illustrated in Figure 4, when the heat transfer area of evaporator varies from 0.5 to 1.0 square meters, a notable change is that the heating COP increases from 3.238 to 3.936, and the compressor power decreases from 2.728 to 2.219 kW. Due to the change of heat transfer area, the mean logarithmic temperature difference reduced from 26.170 to 13.740 K, and the evaporation pressure increased from 2.420 to 3.345 bar, accordingly. As

has been discussed above, the increase of the suction pressure of the compressor is the main factor to improve the energy efficiency of the system.

Furthermore, reference to the model proposed by Chen et al. (2013), a thermodynamic simulation of the heat pump system with a recuperator inserted before the evaporator was carried out, the discharge pressure of the compressor was kept to 13.2 bar, the feed water temperature was 10 °C and the mass flow rate of output water was kept to 0.060 kg/s so that some comparable results were obtained, which is illustrated in Figure 5. Note, the compressor power reduces sharply to 1.549 kW, compared with 2.219 and 2.728 kW. The total heat output consists both of the heat load of condenser and the heat load of recuperator, so the heating COP reaches 5.672, almost doubled compared with the original systems in Figure 4. The heat transfer area of the recuperator was also 0.5 square meters

**Figure 4** | Thermodynamic simulations under different heat transfer area of evaporator conditions.

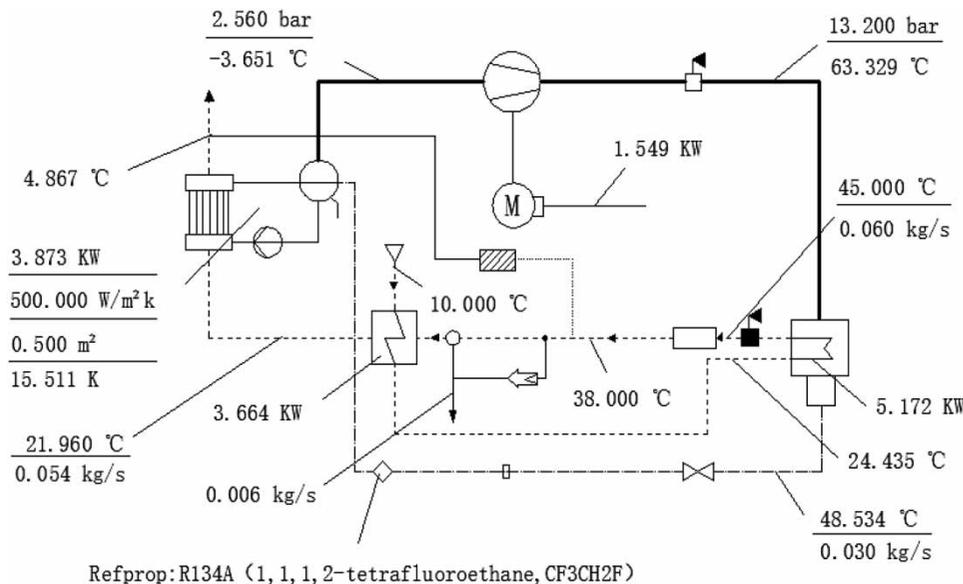


Figure 5 | Thermodynamic simulation of the heat pump system with a recuperator inserted before the evaporator.

or so, so the total heat transfer area for recycling wastewater heat was the same as the original system with a larger heat transfer area of evaporator, but the energy efficiency had been greatly improved. The reason may be that the recuperator improved the exergy efficiency of both the evaporator and condenser by reducing the heat transfer temperature difference. Compared with Figure 4, the condenser heat load in Figure 5 is reduced by about 3.562 kW, which means that heat transfer area and the volume of the heat exchanger can be reduced, which is also an advantage. In summary, configuring a recuperator to the wastewater source heat pump system is the most effective way to improve the hot water output and the energy efficiency.

In addition, the instantaneous wastewater source heat pump water heating and showering system described in this paper needs to consider more details such as start-up, thermal storage, constant temperature control and frequency control. It also needs an inverter compressor and an adjustable throttle to meet the optimum working conditions, the mechanisms discussed above may be helpful to improve the effectiveness of control strategies for the inverter compressor driver and throttle controller.

The above discussion will also be beneficial to the field of some industrial or agricultural water resources management, where water reuse and energy recovery are both needed, e.g. brewery, laundry and marine aquaculture.

CONCLUSIONS

This paper established a thermodynamic model of an instantaneous wastewater source heat pump water heating and showering system. Simulations and analysis were carried out to investigate the energy efficiency and hot water output under different operating conditions. The following conclusions were obtained:

1. If the heat exchange area of the evaporator is limited to 0.5 m², the heating *COP* of the heat pump can reach 3.3, and maintains a constant value at all feed water temperature when the suction pressure and discharge pressure of the compressor is invariable. The compressor power and volume flow rate of outlet water increase with the increasing temperature of feed water.
2. Reducing the suction pressure of the compressor is an effective way to increase the hot water output, but impacts greatly on the heating *COP*.
3. Increasing the discharge pressure of the compressor is not an effective way to increase the hot water output, but impacts little on the heating *COP*, suitable for adjusting the temperature of output water.
4. When the heat transfer area of the evaporator varies from 0.5 to 1.0 square meters, a notable change is that the heating *COP* increases from 3.283 to 3.936 when the feed water

temperature was 10 °C and the mass flow rate of output water was kept to 0.060 kg/s, so increasing the heat transfer area of the evaporator is a more effective way to improve the hot water output and the energy efficiency.

- The heating *COP* of the heat pump system with a recuperator inserted before the evaporator can reach 5.672, which is nearly double that of the original system. So, under the premise of limited heat transfer area, configuring a recuperator to the wastewater source heat pump system is the most effective way to improve the hot water output and the energy efficiency.

Furthermore, we can conclude explicitly that wastewater can not only be reused as a resource, but also can be reused as an energy source.

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REFERENCES

- Chen, W., Liang, S. Q. & Guo, Y. X. 2013 Investigation on the thermal performance and optimization of a heat pump water heater assisted by shower waste water. *Energy Build.* **64**, 172–181.
- Dong, J. K., Zhang, Z., Yao, Y., Jiang, Y. Q. & Lei, B. 2015 Experimental performance evaluation of a novel heat pump water heater assisted with shower drain water. *Appl. Energy* **154**, 842–850.
- Guo, Y. X., Cai, Y. L., Liang, S. Q. & Chen, W. 2014 Experimental study on a shower water heat recovery device in buildings. *Appl. Mech. Mater.* **226**, 2402–2406.
- Kim, M. S., Mulroy, W. J. & Didion, D. A. 1994 Performance evaluation of two azeotropic refrigerant mixtures of HFC-134a with R-290 (Propane) and R-600 (Isobutene). *J. Energy Resour. Technol.* **116**, 148–154.
- McNabola, A. & Shields, K. 2013 Efficient drain water heat recovery in horizontal domestic shower drains. *Energy Build.* **59**, 44–49.
- Pinzón, J. 2013. *Energy Efficiency in Water Reuse and Desalination: Five Individual Projects Which Address Energy Efficiency in both Water Reuse and Desalination*. California Energy Commission, WaterReuse Research Foundation. Publication number: CEC-500-2013-093. Available from: www.energy.ca.gov/2013publications/CEC-500-2013-093/CEC-500-2013-093.pdf.
- Prosin, T., Pryor, T. & Creagh, C. 2015 Hybrid solar and coal-fired steam power plant with air preheating using a centrifugal solid particle receiver. *Energy Proc.* **69**, 1371–1381.
- Wallin, J. & Claesson, J. 2014 Analyzing the efficiency of a heat pump assisted drain water heat recovery system that uses a vertical inline heat exchanger. *Sustain. Energy Technol. Assess.* **8**, 109–119.
- Wang, H. D. 2011 Experimental research on performance of heat pump using shower waste water as heat source. *Key Eng. Mater.* **480**, 887–892.
- Wong, L. T., Mui, K. W. & Guan, Y. 2010 Shower water heat recovery in high-rise residential buildings of Hong Kong. *Appl. Energy* **87**, 703–709.
- Xiao, S. H., Luo, Q. H. & Li, G. F. 2014 Utilizing thermoelectric heat pump to heat recovery of shower waste water. *Appl. Mech. Mater.* **521**, 757–761.

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