Development of Thermoelectric Heat Pump Water Heaters

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Abstract
Experiments verified that a thermoelectric heat pump system is more efficient than an electrical heating device, for its heating coefficient reached more than 1.6 with suitable operating conditions. Two novel instantaneous water heaters were developed and tested successively. The prototype with circulating water pump can save power consumption more than 40% in comparison with conventional electric water heaters, while the prototype integrating with thermosiphon can save more than 38%. Comparing two prototypes, the latter prototype becomes more compact, more technologically advanced and practical, because it eliminated the working life choke-point of the former, while holding the advantages, such as high efficiency, reliability, safety, environmental friendly.

Keywords: TE heat pump; temperature difference; thermosiphon; water heater

1. Introductions
Recently, new materials and synthesis techniques have reawakened interest in the use of thermoelectric (TE) technology [1, 2]. An increasing number and variety of promising TE products have been reported for specific applications in military [3], instrument [4, 5], medicine [6] and other fields [7, 8]. While being utilized for heating, a TE heat pump is an economizing device with high heating efficiency in comparison with a resistance-heating device, especially on suitable temperature conditions [9]. Some TE heat pump devices have been developed such as clothing dryer [10], water heater [11] and incubator [12]. Replacement of conventional heat exchangers by heat pipes or thermosiphons was found to improve the performance of a TE refrigeration device [13, 14]. Adoption of special measures to collect the waste-heat outputs for reuse may increase the efficiency of a TE heat-pump device greatly [15]. Since energy consumption of heating water account for 10~40% of total quantity of different buildings in urban districts, energy efficiency is a prior subject in developing water heaters [16]. Electrical or gas water heaters are essentially high-grade kettles with an insurmountable shortcoming of unsatisfactory efficiency. In the present investigation, a novel instantaneous water heater was developed on the base of experimental study of a TE heat pump system. The prototype presented distinctive advantages of reliability, high efficiency and no pollution, it also bring new ideas on local heating and energy recovering in buildings.

2. Experimental study on a TE Heat-pump.
There is no intrinsic difference between TE refrigerators and TE heat pumps, except for different utilizations. The half Joule heat transferring to the cold end will counteract a fraction of cooling capacity, while the half Joule heat transferring to the hot end will add to the heating capacity, so a TE heat-pump is more efficient than a TE refrigerator. Its maximum performance parameters are following [9]:

\[ \eta_{\text{max}} = \frac{T_h \sqrt{1 + 0.5Z(T_h + T_c) - T_c}}{(T_h - T_c)\left(1 + 0.5Z(T_h + T_c) + 1\right)} \]  

(1)

\[ Q_{\text{h, max}} = \frac{\alpha^2}{R} \left( T_h T_c + \frac{T_c}{2} - \frac{T_h - T_c}{Z} \right) \]  

(2)

The above equations reveal that efforts are significant on three aspects to improve the performances of a TE heat pump, i.e. (i) to gain high figure of merit (Z), (ii) to reduce the junction temperature difference (\(\Delta T = T_h - T_c\)), (iii) to raise the working temperatures \((T_h\) and \(T_c\)) suitably.

An important parameter of thermo-elements is the figure of merit \(Z\), which synthetically characterizes the TE material’s thermal and electrical properties. Up to now, the range of \(Z\) is 1.5~3.0\(\times\)10\(^{-3}\)K\(^{-1}\) for practical applications. If \(\Delta T\) is less than 50°C, the heating coefficient reaches 1.5~7.0, which means that the heat rejection of a TE heat pump equals 1.5~7.0 times of a electrical heating device. More over, the heating coefficient of a cascade TE heat pump can increase further [9].

A TE heat pump testing system was established for experimental investigation to provide basic data of developing a TE water heater. TE modules are sandwiched between heat exchangers manufactured from a type of flat-fin aluminum. Configurations of heat exchangers are alike on hot and cold sides. Tests consist of 3 groups with different parameter variations, namely: (i) flow rate of heat mediums; (ii) temperature difference between heat mediums; (iii) input power. We controlled the temperatures of heat mediums below 55°C to meet the temperature demands of supplying water and to fit in with the operating temperature limit of commercial single-stage TE modules [17]. Further details concerned are discussed in reference [18].
The TE heat pump was more efficient in low load than in high load, however, the relative variation of junction temperature difference \( (T_s - T_c) \) was larger in the former case than in the latter case. The further experiments validated that increasing power input caused decreasing \( \eta \), and the decreasing trend was becoming slow with the increasing power input. The heating coefficient of a TE heat-pump reached 1.6~5.5 if the temperature difference of heat mediums was limited in the range of -10~15°C. In comparison with an electrical heating device, a TE heat pump is more efficient, which brings new ideas on local heating, utilizing low-grade waste heat and energy saving in buildings. The experimental data may be utilized as the base of developing TE heat pump devices.

### 3. TE heat-pump water heater with Circulating Water Pump

#### 3.1 Description of the prototype

As illustrated in Fig.3, The prototype consists of a certain number of TE modules, heat exchangers on hot/cold side, a circulating water pump, a heat recovery exchanger, an electronic circuit package, and other components. TE modules are sandwiched between heat exchangers on hot and cold sides. Some components, such as the electronic circuit package, are not displayed in the schematic diagram for simplicity. The heat recovery exchanger is embedded in the floor to facilitate energy recovering from drainage; it takes up no usable bathroom space.

![Fig.3. Schematic of the TE Heat-pump Water Heater Prototype with Two Flow Paths](image)

When the prototype is powered by a DC source, the system contains simultaneously two flow path as follows: Hot Side: Supplying water, which firstly heated

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Fig.1. TE Heat-pump Performances with Flow Rate Variations of Heat Mediums

Fig.1 reveals TE heat-pump heating performance \( (\eta) \) with respective variations of flow rate of heat mediums. Flow rates on cold or hot side \( (G_c, G_h) \) are correspondingly fixed to 5 l/min or 3 l/min respectively, so Fig.1 presents 4 subgroups of test data. The initial temperatures of heat mediums on two sides were the same and shown in legends of the figure, as well as the power inputs of different subgroups.

Increasing flow rates intensified the heat exchange between exchangers and mediums, and the TE heat-pump performance turned better further. Since heat-flux on hot side is \( [\eta/ (\eta-1)] \) times of the cold side, variation of flow rates on hot side impact the TE heat-pump performance more noticeably than the case on cold side.

![Fig.2. TE Heat-pump Performances with Variations of the Mean Temperature Difference of Heat Mediums \((T_{wh} - T_{wc})\)](image)

Fig.2 displays TE heat-pump performance \( (\eta) \) with variations of the mean temperature difference between heat mediums \( (T_{wh} - T_{wc}) \) on two sides. The flow rates of heat mediums on two sides are both fixed to 6 l/min. The initial temperatures of heat mediums on hot side \( (T_{whi}) \) and the power inputs \( (P) \) of different subgroups are presented in legends.

Increasing mean temperature difference of heat mediums \( (T_{wh} - T_{wc}) \) resulted in linearly decreasing \( \eta \), and the decreasing trend was more remarkable in the case of less power input than in the larger power input. The TE heat pump was more efficient in low load than in high load, however, the relative variation of junction temperature difference \( (T_s - T_c) \) was larger in the former case than in the latter case.

The heating coefficient of a TE heat-pump reached 1.6~5.5 if the temperature difference of heat mediums was limited in the range of -10~15°C. In comparison with an electrical heating device, a TE heat pump is more efficient, which brings new ideas on local heating, utilizing low-grade waste heat and energy saving in buildings. The experimental data may be utilized as the base of developing TE heat pump devices.

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by the heat exchanger on hot side, sprays out of the nozzle, and then gathers into the heat recovery exchanger via orifice of the shell, lastly flows into the drainage; 

**Cold Side:** Circulating water, which firstly absorbs heat from waste water through heat exchanger, is driven by the water pump, then flows through the heat exchanger and is cooled on cold side, and then enters into the heat recovery exchanger again to exchange heat with waste water repeatedly. The heat, which extracted from circulating water, is pumped to the hot side, and heats the supplying water together with the power consumed by TE modules.

The electronic circuit package is provided with functions as follows: (i) AC is converted into an adjustable DC to power the TE modules, and its ripple distortion is maintained to below 10% at all voltage levels. (ii) The temperature of hot water is controlled to meet thermal comfort for various climates. (iii) Safety protections against over-current and over-temperature. (iv) The circulation pump and supplying water are switched on 5 seconds earlier and switched off 5 seconds later than TE modules. (v) Safety protection for bathers in emergencies.

A special iteration program has optimized the matches between heat exchangers and heat-flux on both sides of the TE modules on typical operating conditions.

While designing a TE heat-pump device, it is not normally possible to satisfy two maximum aims simultaneously, namely: (i) rate of energy release or absorption, $Q_c$; (ii) pumping efficiency, $\eta$. Since a water heater is a perennial appliance with large power consumption, a high efficiency is the prior aim.

### 3.2 Efforts to Improve Performances

The smaller the temperature difference across TE modules, the more efficiently a TE heat-pump device operates. As for the system of Fig. 3, the original flow path of the prototype presents two significances: (1) Waste heat is recovered and otherwise wasted by drainage, and heating pollution to the environment is further eliminated; (2) It reduces the temperature difference between heat sink and source ($\Delta T_s$) remarkably and raises the operating temperature of thermoelements ($T_h$ and $T_c$) suitably.

Temperature of bath water is generally below 45°C, and drops to 35 °C or so after shower, so temperature difference between the heat sink and source ($\Delta T_s$) will be less than 10 °C.

Some measures were adopted to reduce the heat-transfer temperature difference between substrates of TE modules and heat mediums: (i) Base plates of heat exchangers were polished, and heat-conducting grease was evenly spread on the surfaces; (ii) Heat exchangers were manufactured from a type of flat-fin aluminum.

The prototype eliminates the majority radiation and conduction losses by improving design and assembly: (i) The surfaces of exchanger substrates were almost full covered by TE modules, so the facing area between exchangers is minimized; (ii) The assembly was fixed together by stainless steel screws with insulating washers to reduce the conductive heat leakage via heat-bridge.

The suitable operating temperature range of commercially available single-stage TE modules is generally -150~80°C\(\text{[17]}\), beyond which its interior structure may be damaged by thermal strain. The substrate temperature of TE modules of the prototype, measured by thermocouples, was lower than 63.1°C on the hot side, when water temperature was below 50°C.

### 3.3 Performance Tests of the Prototype

Performances of the prototype were tested under different operating conditions with reference to the technical criterion of conventional electrical water heaters\(\text{[9]}\).

The tests have been performed in different weathers in Changsha, and the fixed flow rates of hot water were respectively 0.05 kg/s, 0.067 kg/s, 0.083 kg/s and 0.1 kg/s (viz. 3 L/min., 4 L/min., 5 L/min. and 6 L/min.) Experiment results are shown in Fig.4.

The energy efficiency ratio (EER) of the device is defined as the ratio of heat load of heating water to the total power consumption:

$$EER = \frac{G_{w,h} \cdot c \cdot (t_{w,h2} - t_{w,h1})}{P_{TE} + P_{wp}}$$

As can be seen from Fig.4, the EERs reach 1.5 or more, even if the water temperature rising (viz. $t_{w,h2} - t_{w,h1}$) reaches 40°C for different flow rates. In China, technical criterions demand that heating efficiency of instantaneous electrical water can’t be less than 80% (namely, EER must be larger than 0.8). While meeting the temperature demands of hot water in different climates, the prototype can save power consumption more than 40% in comparison with conventional electric water heaters even if heating efficiency of the latter reaches 90% (namely, EER is 0.9) due to technology renovation. The EER is the highest when flow rate is 4 l/min, and the lowest when 3 l/min, moderate when 5 l/min and 6 l/min, which illustrates that variation of flow rate brings noticeably impact on prototype performances.
In order to find out the potential of heat recovery from waste water and to provide basic data for further optimization of the TE heat-pump water heater, the temperature drops of hot water due to shower have been tested at different climate temperatures of 6°C, 10°C, 15°C respectively. The flow rate is 6l/min, and temperature is (42±1)°C before shower, while water temperature is still (35±1.2)°C after shower, and the ratio of heat loss by drainage is about 80%, so the potential of heat recovery is considerable.

4. TE Heat-pump Water Heater Integrating with Thermosiphon

4.1 Description of the prototype

The prototype described in Section 3 contained a choke-point of working life, namely the circulation pump, which is a weak component in comparison with others. Furthermore, the water pump runs with noise, and consumes additional energy.

A novel instantaneous water heater integrating a separating thermosiphon was then developed, and its schematic diagram is in Fig.5. It consists of a certain number of TE modules, heat exchangers on hot side, a separating thermosiphon, an electronic circuit package and other components. TE modules are sandwiched between heat exchangers on hot side and the condensing heat exchanger of the thermosiphon on cold side. The separating thermosiphon is a special wickless heat pipe charged with acetone as working fluid, and it is composed of an evaporating heat exchanger, a vapor pipe, a condensing heat exchanger and a condensed liquid pipe. The evaporating heat exchanger is embedded in the floor to facilitate energy recovering from drainage; furthermore, it takes up no usable bathroom space.

When the prototype is powered by a DC source, the system also contains simultaneously two flow paths: Hot Side: The flow path of supplying water is similar to that of the prototype described in Section 3.1. Cold Side: There exists a circulating phase change in the sealed thermosiphon. The liquid of working fluid, which firstly absorbs heat from wastewater through evaporating heat exchanger, evaporates and the resulting vapor travels to the condensing heat exchanger via the vapor pipe, where vapor of working fluid condenses into liquid while rejecting heat. The liquid then returns to the evaporating heat exchanger via condensed liquid pipe, where it absorbs heat from waste water repeatedly. The heat, which extracted from condensing working fluid of the thermosiphon, is pumped to the hot side firstly, and then heats the supplying water together with the power consumed by TE modules.

The separating thermosiphons presents the following advantages [19]:

(1) Convenience of layout: The evaporating and condensing exchanger can be arranged conveniently for space layout.

(2) Flexibility of configuration: Its evaporating and condensing exchanger can be designed respectively for regulating their heat flux density to match with other components; its combination with TE modules and other components is also flexible.

(3) Simplicity of technology: It is wickless. The inners of evaporating and condensing exchanger can be finned surface.

(4) Suitability for large heat flux: As for an instantaneous water heater, heat recovering from waste water reaches several kilowatts, and its fluctuation is remarkable with variation of operating situations. Since vapor and liquid of working fluid flow via different paths respectively, a separating thermosiphon device may be free from heat-transfer limit by optimizing its design and fabrication.

The functions of electronic circuit is similar to that of the prototype described in Section 3.1.

4.2 Efforts to Improve Performances

The measures to improve performance of the prototype integrating with thermosiphon were also similar to that described in section 3.2.

The thermosiphon is a component with excellent thermal conductivity. The inners of condensing and evaporating exchanger of thermosiphon were both finned surface, and the exterior of evaporating exchanger was embedded into large fin surface and immersed in wastewater.

4.3 Performance Tests of the Prototype

Performances of the prototype were also tested under the similar operating conditions to that of Section 3.3. Experiment results are shown in Fig.6.

The energy efficiency ratio (EER) of the device is defined as the ratio of heat load of heating water to power consumption:

\[
EER = \frac{G_{w,h} \cdot c \cdot (t_{w,h2} - t_{w,h1})}{P_{TE}}
\]
As can be seen from Fig.6, the EERs reached 1.45 or more, even if the water temperature rising (viz. $t_{w2} - t_{w1}$) reaches 40°C for different flow rates. The prototype can reduce power consumption more than 38% compared with ones of the conventional electrical water heaters. The EER is the highest when flow rate is 5 l/min., and the lowest when 3 l/min., moderate when 4 l/min. and 6 l/min.

5. Discussions

5.1 Comparison with TE Cryogenic Coolers

Since the operating temperature range of the most commercial single stage TE modules is -150–80°C, the TE modules would be damaged by thermal stress if their operating temperature is too high or low. As all the physical properties of the TE material are dependent on temperature, the module’s performance increases with temperature over the operating hot junction temperature range, 123K to 353K. The maximum parameters at an optimum hot junction temperature of $T_h$ (K) can be estimated roughly from following equations; the subscript of 300K indicates the parameter based on hot junction temperature at 300K (23°C) [17].

\[
(\Delta T_{\text{max}})_{T_h} = 67 + 0.4(T_h - 300) \tag{5}
\]

\[
(Q_{c,\text{max}})_{T_h} = (Q_{c,\text{max}})_{300K} + 2.0(T_h - 300)G \cdot N \tag{6}
\]

24% increase of the maximum refrigerating capacity and 29% enhancement of the maximum temperature difference can be reached when the hot junction temperature rises from 0°C to 60°C. Compared to conventional TE cryogenic coolers, the performance of the two prototypes can be improved considerably because the operating temperature of thermoelments is higher. In the present investigation, the temperature of hot water was below 55°C, and the hot junction temperature was below 67.3°C.

5.2 Significances on Environment and Energy

As environment protection and energy efficiency are becoming the prior subjects for the sustainable development of societies, investigations on concerned technologies are in the ascendant. TE heat pump devices are extremely simple, have no moving parts, and use no greenhouse gases. It is of great practical significance in building energy efficiency, utilizing low-grade waste heat, supplying hot water and local heating at near room temperature.

It is surveyed that energy consumption of heating water accounts for a remarkable proportion of total building energy consumption in China, specifically, 2.7% to office buildings, 10.7% to shopping centers, 31% to hotels, 41.8% to hospitals and 20% to apartments[16]. The above data reveal that the potential of heat recovering from wastewater is considerable.

5.3 Comparison with Compression Heat Pump Water Heater Using CO2

The TE heat pump water heater and the compression heat pump water heater using CO2 have their respective merits and disadvantages. The COP of the latter may reach 3.0-4.0; however, it is a very complicated system in comparison with the former. The COP of the former may reach 1.5-3.0; however it is environmental friendly, simple and reliable. Its configuration contains no moving parts, and run with no noise. It is powered directly by DC electric sources, such as PV cells, fuel cells; and its configuration becomes simpler in such case.

DC power sources are generally equipped for carriages, ships, planes and other analogous movable spaces, and energy saving may be more important in such spaces than in buildings, so the TE heat-pump water heater is of great practical interest in supplying hot water for such situations.

5.4 Further Improvements

The performance of the TE heat-pump water heater can be further improved by optimizing design and fabrication on the basis of experimental data. The standard flow rate of the prototype is fixed to 6 l/min to meet the shower demands of the majority of people, whereas experimental data illustrate that the EER is the highest when actual flow rate is 4 L/min. for the prototype with circulating water pump, and 5 L/min. for the prototype integrating thermosiphon. Reasons for such results may be following: (i) Since the thermal process of the prototype is fairly complicated, and the tentative design owned no experimental data basis, calculation parameters are not accorded perfectly with actual characters of prototype components; (ii) The fabrication of the prototype was coarse because many machining and assembling works were performed semi-manually or manually. (iii) The remnant air in the thermosiphon hinders working fluid from condensing on the inner surface, which decreases its heat-transfer and further degrades performance of water heater prototype.
6. Conclusions
In comparison with electrical heating devices, a TE heat pump is more efficient for its heating coefficient reached more than 1.6 with suitable operating conditions. It brings new ideas on local heating, waste heat recovering and energy conservation in buildings.

The original flow path facilitated heat recovering from drainage, and reduces the temperature difference between heat mediums remarkably, thus its performance was improved greatly. The former prototype can save power consumption more than 40% in comparison with conventional electric water heaters, and the latter prototype can save more than 38% correspondingly.

In comparison with the former prototype, the latter prototype becomes more compact, more technologically advanced and practical, because it eliminated the working life choke-point of the former, while holding the advantages, such as high efficiency, safety and so on.

The water heater prototype described in this paper has been protected under patent [20].

Acknowledgements
This work has been supported by the National Natural Science Foundation (50408019), the People’s Republic of China.

Nomenclature:
- $C$: the specific heat of water (J/kg • °C);
- $G$: the flow rate of hot medium on cold side (l/min);
- $G_h$: the flow rate of hot medium on cold side (l/min);
- $G_{w,h}$: the flow rate of hot water (kg/s);
- $P_{TE}$: power consumption of TE modules (W);
- $P_{wp}$: power consumption of the circulating pump (W);
- $Q_{c,max}$: the maximum refrigerating capacity (W);
- $Q_{h,max}$: the maximum heating capacity of a TE heat-pump(W);
- $R$: electrical resistance of thermoelements (Ω);
- $T_c$: the temperature of the cold junctions (K);
- $T_h$: the temperature of the hot junctions (K);
- $T_{wc}$: the mean temperature of heat medium on cold side(°C);
- $T_{wh}$: the mean temperature of heat medium on hot side(°C);
- $T_{whi}$: the initial temperature of heat medium on hot side(°C);
- $T_{w,h1}$: the temperature of water entering water heater(°C);
- $T_{w,h2}$: the temperature of water exiting water heater(°C);
- $Z$: the figure of merit (K⁻¹);
- $\alpha$: the Seebeck coefficient (V/K);
- $\eta$: the heating coefficient of TE heat-pump;
- $\eta_{max}$: the maximum heating coefficient of TE heat pumps;
- $\Delta T$: the junction temperature difference (K);
- $\Delta T_{max}$: the maximum junction temperature difference (K);
- $\Delta T_s$: the temperature difference between heat sink and source (K);
- $EER$: the energy efficiency ratio of water heater

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