A Large Temperature Difference Thermal Substation (LTDTS) with Electric Heat Pump and Thermal Storage Tank

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Abstract. A new thermal substation named LTDTS is presented, which could reduce the return water temperature of primary pipeline to below 30 °C. The capacity of an existing heating pipe could be enlarged by more than 50% without changing its flow rate. The LTDTS with single-stage or two-stage heat pump is experimented, which is compared with simulation results. The LTDTS is recommended for large district heating systems due to advantages of reducing the pipe investment and recovering industrial waste heat for lower energy consumption of heating.

Keywords: District heating; Large temperature difference; Heat pump; Thermal substation; Thermal storage.

1. Introduction

It was reported that 0.86 billion tons of coal were consumed by buildings of China in 2015, in which about 0.2 billion tons were used for heating in winter. Meanwhile, the haze is much more serious during the heating period due to significant consumption of fossil fuels in the northern of China. Therefore, how to reduce the energy consumption and pollutant emission of heating is quite necessary and significant at present. Recovering low-grade industrial heat for heating is recommended [1], which could decrease the energy consumption and pollutant emission at the same time. District heating is playing a more and more important role at present, which could decrease the energy consumption and pollutant emission obviously when compared with the decentralized heating system [2]. In addition, the capacity of heating pipes could not satisfy the growing heating demand of new urban buildings. Therefore, a feasible way for increasing the capacity of heating pipe is decreasing the return water temperature. However, the return water temperature of primary pipe (PP) could not be lower than that of the secondary pipe (SP) due to a necessary temperature difference in the conventional heat exchanger.

Many efforts are put on reducing energy consumption by decreasing temperatures of both the supply water and the return water of PP, which is possible for new or retrofit buildings where the floor heating systems could maintain indoor thermal comfort with ultra-low temperature district heating (ULTDH), i.e. a supply water temperature of 35-45°C [3]. Besides, many district heating systems have to handle the demand for both heating and domestic hot water. Therefore, the supply water temperature of PP has to be above 50°C at least [4], which is a key hindrance for ultra-low supply temperature district heating systems. Many efforts are put on raising the supply water temperature by means of a compression heat pump [3,5,6], thus, which could employ a thermal storage tank (TST) at the same time for the purpose of meeting requirements of heating and domestic hot water.
Some studies have introduced control strategies aiming at minimizing energy consumption for district heating system with a domestic hot water demand [7,8]. However, an ultra-low temperature difference of PP is not feasible and economical for a large scale CHP system. The actual temperature of supply water of the PP in a large scale CHP system is about 90-120°C due to its heat insulating material’s temperature limit [9]. However, a necessary terminal temperature difference is needed for a conventional plate heat exchanger (PHE), thus, the return water temperature of PP should not be lower than that of SP [10-11]. Besides, return water temperatures are the same of SP and PP in the directly connected district heating system [12-13]. The absorption heat pump is employed at the thermal substation [3].

2. Principles of LTDTS
The principle of LTDTS is show in figure 1.

![Figure 1. Principle of the LTDTS system.](image)

The temperature of return water of the evaporator can be reduced to below 30 °C. The EHP is on at night only by using the TST, which could reduce running cost by using the city valley electricity. Therefore, running modes of the LTDTS are different at day and night, which are shown in figure 2 and figure 3.

The EHP, P1 and V2 are off in the day mode, and hot water in PP is cooled in the PHE only, then it enters the TST from the topside.

![Figure 2. Principle of day mode of LTDTS system.](image)

![Figure 3. Principle of night mode of LTDTS system.](image)

3. Comparison of Different Stages of EHP in LTDTS
The LTDTS model is built and simulated in the software named Engineering Equations Solver (E. E. S.), which contains built-in modules for cycle performance with logarithmic mean temperature
differences for the evaporator and condenser \[14\]. Required working fluid characteristics of R134a could be found in the published work \[15\].

The mass flow rate of R134a could be calculated by:

$$m = \frac{\lambda_c \lambda_p \lambda_l \nu_l}{V}$$

\(\lambda_c\) and \(\lambda_p\) are the coefficient of compressor volumetric and coefficient of compressor temperature. \(\lambda_p\) is its pressure coefficient, which is 0.96 due to little pressure loss in the compressor. \(\lambda_l\) is its leakage coefficient, whose value is 0.99 in this study \[16\]. The theoretical compressor power could be calculated as follows:

$$w = \frac{m \times (h_{out,c} - h_{in,c})}{\eta_i \times \eta_e \times \eta_m}$$

In which is the mass flow rate of R134a. \(h_{out,c}\) and \(h_{in,c}\) are values of specific enthalpy at the outlet and inlet. \(\eta_i\), \(\eta_e\), \(\eta_m\) are its isentropic, electrical and mechanical efficiencies, assumed 0.84, 0.86 and 0.92, respectively. Comparison of different stages of EHP with R134a is given under the designed working case of 120°C/25°C for PP and 60°C/45°C for SP, and the flow rate of SP is 20 kg/s. The equation could be got according to energy conservation law:

$$Q_{pp} + W_{exh} = Q_{sp}$$

Coefficient of performance (COP) is described as follows:

$$COP = \frac{Q_{esp}}{W}$$

![Figure 4. COP of EHP with different ratios of evaporator load.](image)
![Figure 5. Power of EHP with different ratios of evaporation load.](image)

As can be seen from Figure 4, COP decreases sharply when increasing its ratio of evaporator, which is due to the obvious temperature difference between the evaporation and condensation processes. The highest COP of LTDTS is 8.8 when the ratio is 0.51. As can be seen from Figure 5, due to given heating load of SP, the power of EHP reaches its lowest value when the total EHP system shows its best performance.
Figure 6. Power of EHP with different stages of EHP.
Total power of EHP with different stages is compared in figure 6, and the LTDTS selects the process with two-stage EHP as shown in figure 7.

4. Experiments of LTDTS
The experimental apparatus for the LTDTS, as shown in figure 8, is mainly composed by a PHE, a TST and two EHP. A condenser, an evaporator, a scroll compressor and an expansion valve are included in each EHP, whose designed heating load of the condenser is 10kW.

All measuring points are shown in figure 9. Precisions of measuring instruments are shown in table 1.

Table 1. Precision of measuring instruments
| Parameter               | Measuring instrument          | Precision |
|-------------------------|-------------------------------|-----------|
| Temperature             | T-type thermocouple           | 0.1 °C    |
| Pressure                | Pressure transducer           | 0.2%      |
| Mass flow rate of water | Mass flow meter               | 0.5%      |
| Compressor power        | Power transducer              | 1%        |

Temperatures of PP at inlets and outlets of all heat exchangers under a steady working case is show in figure 10. The radiator is widely used for residential heating, thus, temperatures of supply and return water of SP are 60°C/45°C. In order to justify the advantage of two-stage EHPs in LTDTS when compared with the single stage, two experimented EHPs could be switched to the parallel mode or series mode. The flow rates of PP and SP were 0.4 m³/h and 2.1 m³/h, respectively.
The hot water in PP is cooled by 36.5°C in the PHE as shown in figure 10. Temperatures of SP are shown in figure 11. Table 2 compares the simulation results with the experimental results.

**Table 2.** Comparison of simulation and experiment (EHP in parallel).

| Parameter                              | Simulation | Experiment |
|----------------------------------------|------------|------------|
| Inlet temperature of PHE (PP)          | 87.9°C     | 87.9°C     |
| Outlet temperature of PHE (PP)         | 51.4°C     | 51.4°C     |
| Outlet temperature of EHP (PP)         | 35.0°C     | 34.6°C     |
| Inlet temperature of EHP (SP)          | 45.5°C     | 45.5°C     |
| Inlet temperature of PHE (SP)          | 51.0°C     | 51.0°C     |
| Outlet temperature of PHE (SP)         | 57.3°C     | 57.4°C     |
| COP                                    | 6.7        | 6.1        |

LTDTS with two-stage EHPs was also experimented, and the return water temperature of PP is much lower than that of single stage, which can be decreased to 27.2°C as shown in figure 12.

**Table 3.** Comparison of simulation and experiment (EHP in series).

| Parameter                              | Simulation | Experiment |
|----------------------------------------|------------|------------|
| Inlet temperature of PHE (PP)          | 87.8°C     | 87.8°C     |
| Outlet temperature of PHE (PP)         | 54.7°C     | 54.7°C     |
| Outlet temperature of EHPa (PP)        | 36.7°C     | 36.7°C     |
| Outlet temperature of EHPb (PP)        | 27.2°C     | 27.2°C     |
| Inlet temperature of EHPa (SP)         | 37.0°C     | 37.0°C     |
| Inlet temperature of EHPb (SP)         | 44.8°C     | 44.8°C     |
| Inlet temperature of PHE (SP)          | 54.3°C     | 54.3°C     |
| Outlet temperature of PHE (SP)         | 60.4°C     | 60.4°C     |
| COPa                                   | 6.1        | 7.1        |
| COPb                                   | 6.4        | 6.4        |
5. Conclusions
An advanced form of thermal substation called LTDTS is presented and experimented. The heating capacity of an existing district heating system could be increased by more than 50%. Besides, low temperature return water can also recover various industrial waste heat, which can decrease the energy consumption of district heating. The return water temperature of PP is 35°C for the single-stage, which is 26.8°C for the two-stage configure.

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