Exploring active heat exchanger technology applied in substations of district heating systems for energy conservation

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Contents

1 CONCEPT

Existing problem on district heating system

According to the data from Danish Energy Agency, 30 to 40 per cent of total Danish energy consumption is used for heating, ventilation and lighting in buildings in Demark. Among this energy, the biggest part is used for heating of buildings. At present, 60% of all households are heated with district heat from district heating plants and cogeneration plants. Hence, efficient district heating system plays an important role on energy saving and greenhouse gas emission.

In district heating systems, the supply and return water temperature have a big impact on the heat production and energy saving of the systems. At a given supply water temperature, lower return water temperature (increase Δt of the supply and return water temperature) reduces both energy used for water transportation and heat loss during the water distribution. It could also increase the heat recover from flue gas condensers at heating plans. The energy saving potential by increasing Δt is significant. The annual average supply and return water temperature in current district heating systems are in the range mostly from 75 to 100 °C and from 40 to 50 °C respectively (Frederiksen and Werner, 2013). According to the investigation of Frederiksen and Werner (2013), around 7 to 10% of the annual cost reduction can be achieved in a district heating system by reducing the return water temperature of 10 °C.

The return water temperatures in district heating systems depend on cooling processes for the heat carrier in each substation. Based on the data of the 142 measured district heating systems (Frederiksen and Werner, 2013), the theoretical annual supply and return temperature for a typical substation with the current substation technology was 69 and 34 °C. To reduce the return water temperature of a district heating system, the return water temperature from each substation must be reduced further. However, the current technology of substations used passive heat exchangers to transfer heat from a primary district heating network to local customer heating networks. The return water temperature of the substation depends on the temperatures of water returned from the radiators which is limited by the room air temperature of the heated space. Due to such limitation, the return water temperature from each substation is hardly lower than 30 °C.

Solutions

The active heat exchanger is an innovative design on the substation to maintain normal operation conditions of the radiators for space heating and decrease the return water temperature to the district heating network by 5 to 10 °C.

This design uses the fact that the supply water temperatures of district heating networks are usually tens of degrees higher than what are needed by the radiators for the room heating. Instead of decrease the supply water temperature by a passive heat exchange, the active heat exchanger utilizes the exergy of supply hot water to drive an ejector heat pump to cool down the return water and extract heat for heating the supply water of the radiators. The decrease of exergy of the supply hot water by driving the ejector heat pump does not lose heat of the supply water but convert high temperature heat to the heat of low temperature which is exactly what is required for room heating. Such a design makes full use of both energy and exergy of the supply hot water from district heating systems.

2 MAIN OBJECTIVES OF THE PROJECT

The main objectives of this project is to design and develop a small prototype unit of the Active heat exchanger that is driven by the exergy of the supply hot water and test the feasibility of the design concept.

3 SUMMARY OF ACHIEVEMENTS

3.1 Main achievements and lessons learnt

Main achievements

- A real system of the active heat exchanger was developed and tested. The experiment confirmed the feasibility of the design concept.
- The experiment validated that normal plate heat exchangers can be used in this device as generator, evaporator and condenser.
- A low cost diaphragm pump can be used as the work fluid pump in this device. The power consumption of the pump is less than 10 W. This power is the only electric driving force of the whole active heat exchanger which is less than 0.4% of the total heat transfer.

Main lessons learned

- The design and manufacture of the ejector is a key for the development of this technology. The ejector design depends on the capacity of the system, the work fluid and the operating pressure. There are no commercially available ejectors suitable for this application. Huge effort has been invested in this project to search for the ejector and, eventually, the ejector has to be designed and manufactured by ourselves. Since the design and manufacture of the ejector requires special knowledge, skills and experimental facility on aerodynamics and a lot of experimental time, the designed ejector using the limited fund from this project is obviously not optimized and requires to be improved.
- Since each ejector is optimized for a particular work fluid operating at a particular pressure and flow rate, an ejector array may be used when designing a real system in order to adapt to the variation of the load.

3.2 Detailed description of the development

3.2.1 System design

The design of the active heat exchanger is very simple and low cost for construction. Figure 1 shows the principle of the design. Compared to a conventional substation with an indirect connection of a hydronic space heating system, the new design of substation has also a heat exchanger) but add an ejector heat pump. The whole substation includes three loops - the primary water loop (district heating network in red color), the secondary water loop (customer heating network in blue color) and the refrigerant loop of the ejector heat pump (in black color). The primary hot water from district heating network exchanges heat first in the generator (1) of the ejector heat pump. After exchange heat in the generator, the temperature of the primary water is decreased by 20 to 30 °C. The primary water further exchanges heat in the heat exchanger (2) with the secondary water loop to heat up the customer local water to the radiators and the temperature of the primary water is cooled a further 20 to 30 °C. At the end, the primary water exchanges heat in the evaporator (4) of the ejector heat pump and is cooled for another 10 °C or more. After cooling by the generator (1), heat exchanger (2) and evaporator (4), the temperature of return primary water that goes back to the district heating network drop down to 23 °C or lower which is 5 °C lower than the min temperature of the return primary water in a conventional substation. The secondary water in the customer heating network gets heat from both condenser (3) of the ejector heat pump and the heat exchanger (2). The heat obtained from the condenser is a sum of the heat obtained from generator (1) and evaporator (4). Thus, all the heat released from the primary water of the district heating network is transferred to the secondary water of local customer heating network without any loss of the heat energy. However, Δt of the district heating network increase by 5 °C or more.

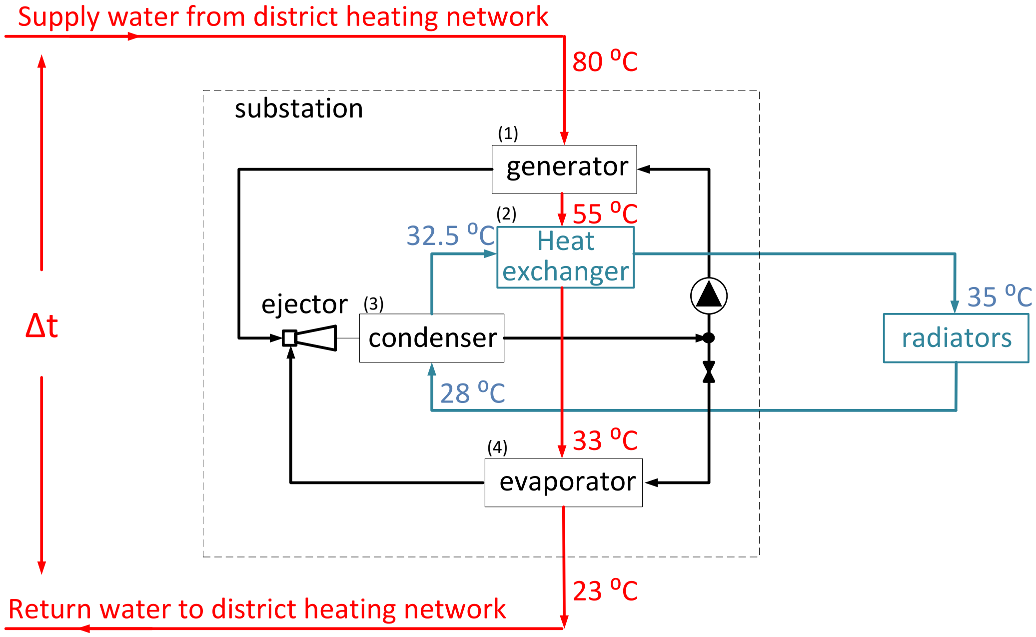

Figure 1. Schematic diagram showing the principle of the innovative substation design using active heat exchanger. The temperatures indicated in different location of the substation are the expected values of the design, which are to be validated and optimized in the project.

The innovation of this design is that it combines an ejector cooling cycle with a heat exchanger. The ejector refrigeration technology is simple, low cost and the mechanism is well understood. It is particularly suitable for the application in a house substation to transfer actively the heat from low temperature return primary water to high temperature supply secondary water. Such a heat transfer from low temperature water to high temperature water is driven by the heat from district heating network and the driving heat is, afterwards, transferred into the secondary water for room heating.

3.2.2 System development

3.2.2.1 Selection of working fluid

The criteria of the working fluid selection were the ODP, GWP, pressure, flammability, toxicity and availability. HFC refrigerant R245fa was selected as the working fluid of this test unit based on its zero ODP, low GWP, low pressure and flammability, non-toxic and relatively low price in the market.

3.2.2.2 Design of the ejector

The ejector is the core of the system development. The ejecting system is equivalent to a heat pump driven by the supply hot water and extracting heat from the return water for heating. The performance of the ejector heat pump determines the performance of the whole system. A market search was made to find a suitable ejector for this project. However, it was found that the ejector suitable for this project was not commercially available. The reason is that very few commercial ejector was designed for a small system of 2-3 kW application. Even if a small test ejector was found from Danfoss, is was not designed for using R245fa as working fluid. Therefore, the first big problem encountered was to design and manufacture an ejector for a 2-3 kW heat pump using R245fa as work fluid.

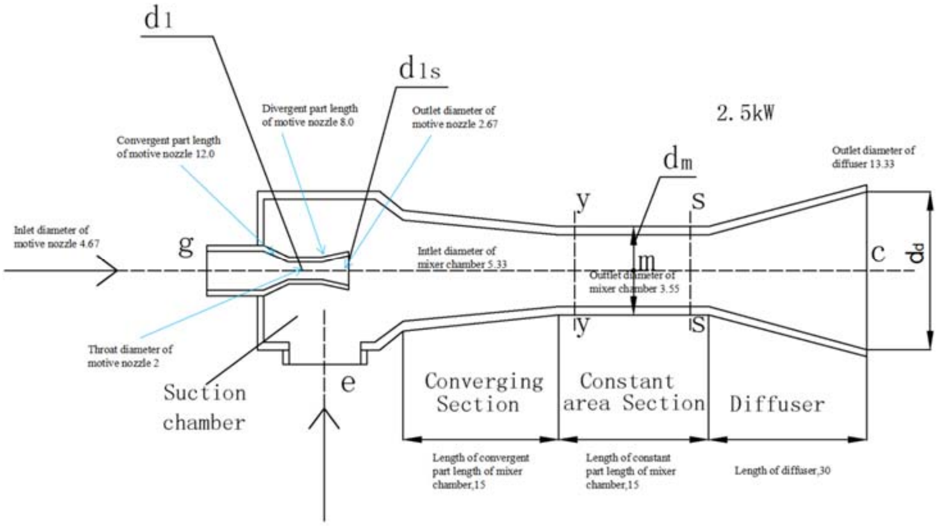

Figure 2. The key dimensions of the ejector based on theoretical calculations.

Using the physical model of ejector and the thermodynamic performance of R245fa (Li et al. 2000 and Zhang et al. 2010), the physical dimension of an ejector was calculated for this project (Figure 2).

Based on the calculation, a prototype ejector was designed as shown in Figure 3. To optimize the performance of the ejector by experiments, the position of the ejection nozzle in the prototype ejector was designed with a possibility of adjustment to change its relative position with the induction intake (Nozzle adjustment in Figure 3).

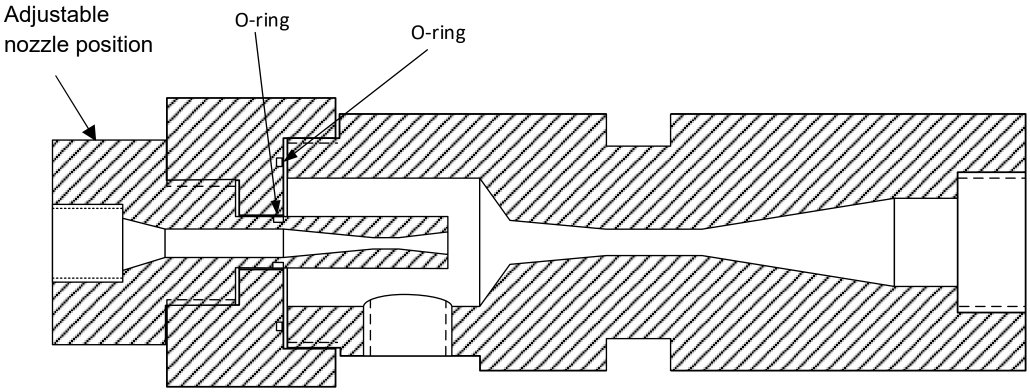

Figure 3. The real design of the ejector with adjustable nozzle position.

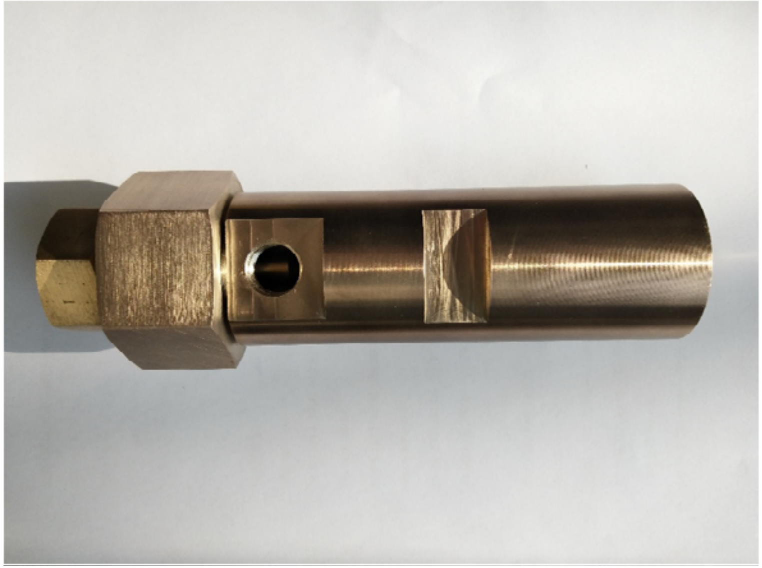

Figure 4. Picture of the manufactured ejector.

3.2.2.3 Selection of components

Danfoss plate heat exchangers were selected for all the heat exchangers, generator, evaporator and condenser used in the prototype unit. Swagelok multi-turns needles were selected as the expansion valves for both evaporator and generator for a very fine tuning of the work fluid flowrate. A high pressure diaphragm pump was selected as the working fluid pump. The pump was driven by a DC motor that can be used to adjust the system pressure and the flowrate of the work fluid. The pump is extremely low cost and very quiet.

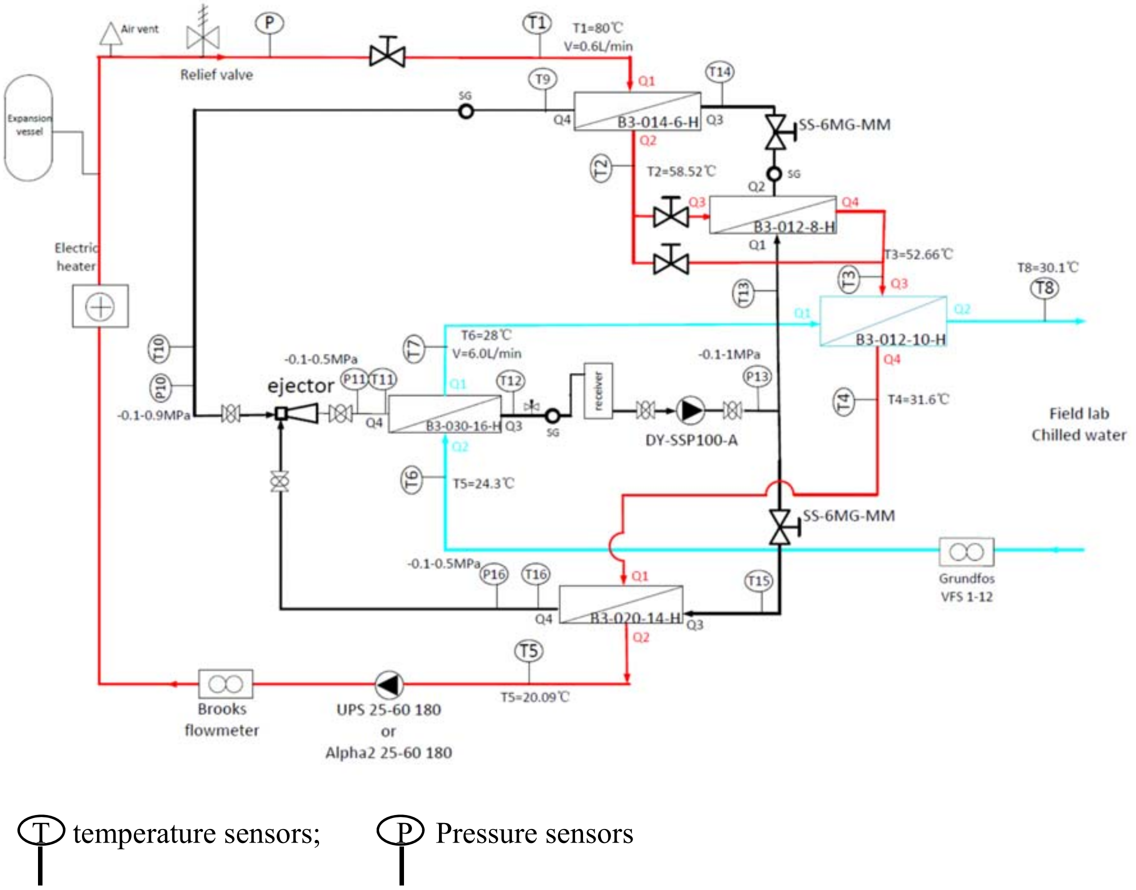

Figure 5. The design of the test unit for the experimental evaluation. The temperature and pressure values at each points of the system were calculated based on a theoretical simulation of the system.

3.2.2.4 Construction of the prototype test unit

After some pre-tests, the design of the test unit was slightly modified from the original concept and fixed as shown in Figure 5. The main change of the design was that the work fluid pump was moved before the two expansion valves. This will guarantee enough pressure across the expansion valve of the evaporator so a commercially available multi-turn needle valve can be used as the expansion valve. Another modification was that a preheater was added before the generator. The preheater heats up the temperature of the work fluid to the evaporating temperature of generator before the fluid reach the generator. This will guarantee a complete evaporation of the work fluid inside the generator. Figure 6 is a picture of the prototype test unit developed for the experiment. Temperature, pressure and flow sensors were installed in all locations that need to be monitored. A computer and an Agilent data logger were used to automatically monitor and control the whole system (Figure 7).

Figure 6. The developed prototype test unit.

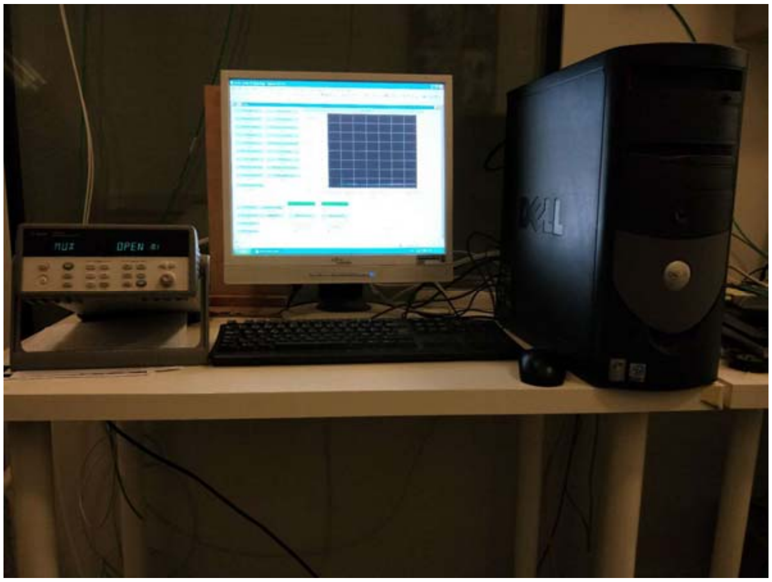

Figure 7. Control and monitor of the active heat exchanger system.

3.2.3 Experimental validation

The test unit as shown in Figure 5 has three circuits i.e. primary hot water circuit simulating the hot water from the district heating network (indicating in red color); user heating supply circuit simulating user heat consumption (indicating in blue color) and working fluid circulation in the heat pump (indicating in black color).

In the experimental test, the primary hot water was heated by an electric heater to provide hot water of 80 °C. The temperature of supply hot water was controlled by the control computer with a stability of ±1°C. The 80 °C hot water was used as the heat source to generate high pressure work fluid gas for ejection. The user heating supply circuit received heat from the condenser of the ejector cycle and the primary hot water after generator. The heat was rejected to the chilled water system of the lab mimicking the load of the user radiator or floor heating system. The return water from the primary circuit was cooled by the evaporator of the ejector heat pump before it was pumped back to the electric heater.

The experimental data collection was conducted when the whole system reach to steady state balanced conditions.

Table 1 to 3 show the main results measured in the experiment. Table 1 and 2 show the temperature data of both water and refrigerant measured at a typical operation condition using the prototype test unit. Table 3 shows COP of the ejector heat pump and the return water temperature in relation to the supply hot water temperature.

Table 1. Measured water temperature (°C) at different locations (see Figure 5).

T1	T2	T3	T4	T5	T6	T7	T8
80.1	56.4	46.3	24.8	21.6	20.9	24.0	28.1

Table 2. Measured refrigerant temperature (°C) at different locations (see Figure 5).

T9	T10	T11	T12	T13	T14	T15	T16
49.2	49.1	35.7	21.5	22.3	42.5	20.2	21.6

Table 3. COP of the ejector heat pump and return hot water temperature in relation to the supply hot water temperature.

Supply hot water temperature (°C)	COP of ejector heat pump	Return hot water temperature (°C)	Difference between supply and return hot water temperature(°C)
77	1.074	25.8	51.2
80	1.080	26.3	53.7
83	1.082	27.2	55.8
85	1.079	27.3	57.7

4 DISCUSSION AND RECOMMENDATIONS

The experiment proved that the designed active heat exchanger could operate continuously with a stable ejection heat pump operation. However, the results of the experiment showed that the temperature of return supply hot water was hardly reach to the designed level of 20 °C. A closed investigation on the designed system and all the components selected was conducted. It was discovered that the reason for this was mainly due to the pressure of the work fluid after generator was not high enough to drive the ejector. Further investigation found that there was an error on the calculation of the plate heat exchanger made by Danfoss when selecting the heat exchanger. This lead to the heating capacity of the generator 30% lower than the designed capacity. Calculation showed that by increasing 30% heating capacity, the evaporating temperature of the work fluid in the generator could increase 2-3 °C that could increase the pressure of the work fluid by 0.2-0.3 bar. This will increase the condensing temperature and decrease evaporating temperature to cool the return water further.

It seems that there is also rooms for further improving the performance the ejector. However, developing a high performance ejector for this application itself is a project that requires a substantial amount of investment. The funding obtained in the project is too limited to perform an optimization work on the ejector development.

The experiment showed that the COP of the ejector heat pump did not increase significantly with increasing temperature of the supply hot water when the temperature of supply hot water increase from 77 to 85 °C. The return hot water temperature increased slightly with increasing supply hot water temperature. However, the temperature difference between supply and return hot water temperature increased significantly with increasing supply hot water temperature, which indicated the advantage of high temperature driving of the ejector heat pump. The experiment further found that when the temperature of supply hot water lower than 77 °C, the pressure at the outlet of the generator decreased dramatically that resulted in the stop of ejection heat pump. Therefore, application of the active heat exchanger requires that the supply hot water temperature does not lower than 77 °C. This means that the ejector heat pump may not work when the water temperature of the district heating network is too low. However, the low limitation of the water temperature of a district heating system is still remained to be determined after the ejector is further improved.

Another phenomenon observed from the experiment was that the system needed to be pre-warmed before starting the work fluid pump. If the temperature of the evaporator is too lower, it may result in the work fluid condensed inside the evaporator and the ejector heat pump could not be started. It is recommended that both evaporator and condenser be emptied before staring the work fluid pump.

It is recommended that a further research on optimizing the design of the ejector for the active heat exchanger is required to validate the value of this technology in practice.

5 REFERENCES

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