Author(s): Kuosa, Maunu; Rahiala, Sirpa; Tallinen, Kirsi; Mäkilä, Tapio; Lampinen, Markku; Lahdelma, Risto; Pulkkinen, Lasse

Title: Mass flow controlled district heating with an extract air heat pump in apartment buildings: A practical concept study

Version: Final draft

DOI: https://doi.org/10.1016/j.applthermaleng.2019.113745

Please cite the original version:
Kuosa, M., Rahiala, S., Tallinen, K., Mäkilä, T., Lampinen, M., Lahdelma, R., Pulkkinen, L. (2020) Mass flow controlled district heating with an extract air heat pump in apartment buildings: A practical concept study. Applied Thermal Engineering, vol 157, 5 July 2019, 113745. Elsevier.

Tekijä(t): Kuosa, Maunu; Rahiala, Sirpa; Tallinen, Kirsi; Mäkilä, Tapio; Lampinen, Markku; Lahdelma, Risto; Pulkkinen, Lasse

Otsikko: Mass flow controlled district heating with an extract air heat pump in apartment buildings: A practical concept study

Versio: Final draft

DOI: https://doi.org/10.1016/j.applthermaleng.2019.113745

Käytä viittauksessa alkuperäistä lähdettä:
Kuosa, M., Rahiala, S., Tallinen, K., Mäkilä, T., Lampinen, M., Lahdelma, R., Pulkkinen, L. (2020) Mass flow controlled district heating with an extract air heat pump in apartment buildings: A practical concept study. Applied Thermal Engineering, vol 157, 5 July 2019, 113745. Elsevier.

Mass flow controlled district heating with an extract air heat pump in apartment buildings: a practical concept study

Maunu Kuosa[a,] *, Sirpa Rahiala[a], Kirsi Tallinen[a], Tapio Mäkilä[b], Markku Lampinen[c], Risto Lahdelma[c], Lasse Pulkkinen[a]

[a] South-Eastern Finland University of Applied Sciences, Pääskysentie 1, 48220, Kotka, Finland

[b] Energianhallinta Tapio Mäkilä, Betaniankatu 4, 20810 Turku, Finland

[c] Aalto University, Department of Energy Technology, P.O. Box 14400 Aalto, Finland

maunu.kuosa@xamk.fi, sirpa.rahiala@xamk.fi, kirsi.tallinen@xamk.fi,
tapio.makila@energianhallinta.com, markku.lampinen@aalto.fi, risto.lahdelma@aalto.fi,
lasse.pulkkinen@xamk.fi

Abstract

Low-temperature district heating (DH) with ring network and mass flow control was constructed and monitored in an existing apartment buildings in Kaarina, Finland. The extract air heat pump was connected in parallel to the area heating. Implementation of the new concept was successful. The study shows the right functioning of the system. The share of DH was 45% in the monitoring period and the rest of the heating was generated by the heat pump. The main result of the study is the practical construction of the new type of control and network planning strategy for the first time in practice after a series of research steps. Mainly, the practical study was in line with the theoretical results.

Keywords: Low-temperature, district heating, ring network, mass flow control, heat pump, concept study

*Corresponding author

Nomenclature

A	heat exchanger surface area, m^2
c_{min}	minimum heat capacity rate, W/K
c_p	specific heat capacity, J/(kgK)
q_m	mass flow rate, kg/s
U	overall heat transfer coefficient, $W/(m^2K)$
ΔT	temperature difference, K
Φ	heat flow, heat transfer rate, W
Φ_{max}	maximum heat transfer rate, W

Abbreviations

AB	apartment building
CHP	combined heat and power production
COP	coefficient of performance
CW	cold water
DH	district heating, detached house
DHC	district heating and cooling
DHW	domestic hot water
eValvomo	Schneider Electric eValvomo Internet program
FC	frequency drive
HP	heat pump
HS	heating station
HW	hot water
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Analysis
LS01	domestic hot water heat exchanger
LS02	heating heat exchanger
LTDH	low-temperature district heating
NTU	number of transfer units
P	water pump
PD	pressure difference
PHE	plate heat exchanger
TI	temperature indicator

1. Introduction

The utilization of district heating (DH) in buildings is at magnitude of 10% in the world as well as in the European Union, but implementation rates vary with respect to countries [1]. Some countries have almost no district heating systems, while other countries have implementation rates of over 50% [1]. Currently, European countries are the leading users of district energy systems [2].The proportion of heat supply from fossil fuels is still very high, both in the world (90%) and in the European Union (70%), since fossil fuels are still the main energy supply group for both combined heat and power (CHP) and boiler plants. To reduce future carbon dioxide emissions from these plants, new non-fossil heat sources must replace the current fossil fuel-based plants [1]. Recent surveys have shown interest in the use of renewables in district heating systems [3], [4]. With sustainability and climate change being a topic of major concern today, emphasis on policies that encourage a reduction in CO_2 and other greenhouse emissions should be a must [2].

The fundamental idea of district heating is to use local fuel or heat sources that would otherwise be wasted in order to satisfy local customer demands for heating by using heat distribution network pipes as a local market place [5]. Thus, the primary merit of district heating is lower heating cost when international fuel prices are high [1]. Traditional excess heat resources are combined heat and power (CHP) plants, waste-to-energy plants, and industrial processes. A combination of heat recycling and renewable heat is the current focus for DH systems [1]. District energy systems are often more environmentally beneficial and financially reasonable when limited retrofit is required. Furthermore, the design of DH systems should include economic and environmental considerations, not solely the efficiency [2].

District energy systems have a higher efficiency when compared with individual heating and cooling [2]. The most important factor affecting exergy losses are the supply and return temperatures [6]. According to [1] district heating and cooling systems have strong potentials to be viable heat and cold supply options in the future world. However, development of the district heating systems is needed to fulfill the future requirements. One important effort is to enhance the current district heating technology so that it aligns with future conditions associated with renewables and buildings with a low heat demand [1]. The next fourth generation DH technology must consider other feature characteristics of renewables and buildings with low heat demands [7]. Furthermore, district heating and cooling systems are often integrated with components such as absorption chillers, cogeneration, and thermal storage to increase their efficiencies. They can improve the soundness of any district heating or cooling installation [2].

A major challenge will be to provide heat with low temperatures in existing buildings [8]. The utilization of lower temperatures reduces transportation losses in pipelines and can increase the overall efficiency of the total energy chains used in district heating [9]. For existing buildings with old radiators, low-temperature district heating (LTDH) can meet the space heating demand for a certain amount of time of the year, while the supply temperature needs to be increased during the cold winter period [10]. Analysis of both the demand and supply sides and their interactions are key in minimizing the primary energy use in buildings [11]. To achieve maximum efficiencies, the demand side (buildings) must be fitted to allow the use of low temperatures supplied by the network. To ensure consumer thermal comfort while saving energy and reducing network return temperature, the hydronic system in the space heating loop needs to be properly designed and operated [9]. New systems should be built according to this new LTDH district heating technology, and existing systems should be transformed during the coming decades. Furthermore, low-temperature heating can be integrated into district heating through, e.g., the use of efficient large-scale heat pumps, solar thermal collectors, and biomass-fired combined heat and power plants [9].

On the transfer side of the DH system, one solution is to move from traditional network design to the use of a completely new concept of mass flow control. District heating by mass flow control is a heating concept in which the heating is carried out by a ring network where the primary and secondary flows of the consumer are provided with speed-controlled pumps to enhance the heat transfer and lower the return temperature. It replaces the traditional system, where the flow of water is throttled at consumer points with control valves. The method achieves clear benefits in implementing a low-temperature network.

This study is the final step in the implementation of the novel technology. The earlier steps were the following. First, the novel DH model was introduced for the first time in 2013 by Kuosa et al. [12] in a static study of traditional and ring networks. In that study, other technologies were discussed as well. The new flow rate was 46%, the pressure loss 25%, and the pumping power 12% of their former values in the pipes. Second, Laajalehto et al. [13] researched a practical application of the new concept in a case study. A real loop-like DH network in Helsinki was simulated using a commercial calculation application. As a result, the total energy losses within the heating season were reduced from 4.4% to 3.1% compared to traditional DH systems. Third, the operation of a plate heat exchanger (PHE) in a consumer substation was studied corresponding to the dynamic operation of the ring network model and finding high heat exchanger efficiency as a result. The key performance factors of the heat exchanger, NTU (=AU/C_{min}), and effectiveness (=Φ/Φ_{max}) were 9.2 and 0.9, respectively [14]. In the fourth step, Iturralde et al. [15] experimentally demonstrated the feasibility of the DH concept. A laboratory-scale system was used to carry out a series of measurements simulating the operation of a consumer substation in a medium-sized apartment building and corresponding to different outdoor temperatures. Nonlinear supply and return temperature curves were obtained, which implies a higher temperature difference (temperature cooling) and lower return temperatures. Finally, the low-temperature DH with the ring network and mass flow control was constructed and monitored in existing apartment buildings in Kaarina, Finland.

Therefore, in this work, a new heat distribution concept was designed and constructed for the first time in practice on the primary side, i.e. on the DH network. The new heat distribution concept contains the ring network, speed controlled pumps (mass flow control), and the heat pump.

In addition, the research is part of a program called “Low-temperature district heating for future energy systems,” which is an international co-operative work in the framework of the International Energy Agency (IEA) in the Technology Co-operation Programme on District Heating and Cooling, including the Combined Heat and Power (DHC/CHP) Annex TS1 [12]. The IEA-DHC collaboration program is the only international research cooperation concerning district heating and cooling [1]. In the project various case studies were analyzed. Examples of low-temperature district heating case studies were presented in Hyvinkää (Finland), Lystrup (Denmark), and Ludwigsburg and Kassel Feldlager (Germany) [9].

Future DH technologies are defined as fourth-generation DH systems, which are low-temperature DH networks with low-energy buildings as well as smart electricity grids. The primary supply temperature is normally below 60 °C but is higher in winter periods [12].

In the current work, the earlier theoretically developed ring network concept was connected to low-temperature area heating with a common exhaust air heat pump. New case-specific DH water temperature curves (on the primary and secondary sides) and the pump control strategy [12-15] was put into practice in the full-scale system.

Due to the deficiencies of the used energy tracking system, several expectations of the system operation are described based on earlier research steps; the corresponding points are generally based on these steps in the right contexts.

2. Methods

2.1 Ring network and mass flow control

In a traditional DH network design, the pipe length between the heating plant and different consumers vary. Unlike the traditional network, a topology based on the ring network uses equal pipe lengths for all consumers. Fig. 1 shows the traditional (a) and ring networks (b) in an area of nine detached houses (1-9, DH) and two apartment buildings (1-2, AB) [13]. The idea of ring topology is to have an equal pipe length for every consumer, as presented in Fig. 1 (b). The supply line begins with the heat station (HS) and ends with the last consumer, as in the traditional network design. However, the return line begins with the first consumer and ends at the heat station. In both the supply and return lines, DH water circulates in the same direction. The network equalizes the pressure differences between the supply and return lines and the consumers [16].

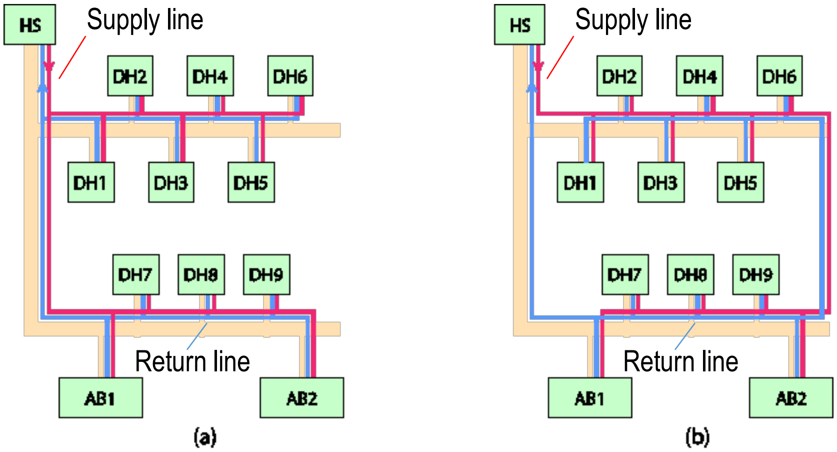

Fig. 1. (a) Traditional district heating network design and (b) ring network design with supply and return lines [13]. The wider lines are roads, HS is a heating station, DH is a detached house, and AB an apartment building.

In a traditional DH system, the secondary side, i.e., the building heating system, is operated using self-acting control valves and a circulation pump. The supply water temperature on the secondary side is adjusted as a function of the outdoor temperature to meet a certain heating demand. To keep the supply water temperature at the desired value, the primary side flow to the heat exchanger is controlled using a motorized valve. Pressure and the supply temperature in the whole DH network are generated and adjusted at a centralized location, usually the heat production plant. Actual customers' pressure differences and supply water temperatures depend on their locations in the network [16].

The mass flow control concept refers to a system where both the primary and secondary side flows are adjusted with inverter-controlled pumps instead of control valves in ring networks [12]. The flow adjustment is carried out by controlling the rotation speed of the pumps (Fig. 2). When heat is not required in a building, the minimum speed of the pump is 10 Hz and the pressure losses of the substation block the flow through the substation [16].

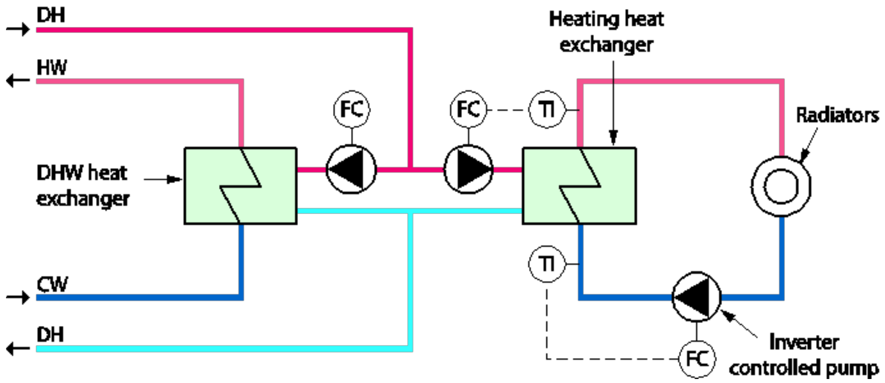

Fig. 2. Mass flow concept. The secondary side and primary side pumps are controlled to receive equal flow rates and temperature differences for primary and secondary sides of the heating heat exchanger. [13]

During the heating season, the line (balancing) valve (the one, e.g., in the return line in Fig. 4) causes enough resistance to the pump so that a 10 Hz cycle cannot drive water through the heat exchanger. When the heating stops for a season, the pumps and water flow stop on the heating side.

The philosophy of controlling the pumps (Fig. 2) is presented in [13]. The idea of the new pumping system is not only to overcome pressure losses in the substation but also to function as weather compensators by adjusting the secondary side temperature levels according to outdoor temperatures [16].

Systems based on mass flow control have previously been implemented in buildings, i.e., on the secondary side, and have made significant savings [17], [18]. In this project, a new heat distribution concept was designed and constructed for the first time in practice on the district heating network, i.e., on the primary side after theoretical research steps [16], [19], [20].

2.2 Construction of a low-temperature area heating

A number of issues need to be addressed in regard to matching the demand by space heating and domestic hot water (DHW) on the building side with the available energy from the supply side in order to develop advanced low-temperature heating networks [9]. System functioning is based on heat flow (Φ) that is distributed. It is calculated by the product of the mass flow rate (q_m), the specific heat capacity (c_p), and the temperature difference (ΔT) of DH water between the supply and return pipes [1], i.e.

$$\Phi = q_m c_p \Delta T. \tag{1}$$

The DH network and modeling of the heat distribution center were made in an existing heating system in Kaarina, Finland. The Vahakas residential quarter has six blocks of flats (110 flats, with total of 6,394 square meters and 26,600 cubic meters of building space).

The apartment buildings and the ring network are presented in Fig. 3. Heat was brought to the area from an existing high-temperature DH network. The supply lines are red and the return lines blue. Network heating and preparation of the DHW were carried out by taking heat from the high-temperature network by using heat exchangers of 307 kW and 410 kW, respectively (Fig. 4). These heat exchangers were in the common heating station placed in the building "Harmaa" (Fig. 3). Speed-controlled pumps were installed on the primary and secondary sides of house-specific heat exchangers for space heating. One hydronic transmission pump was installed in the ring network to adjust the pressure level of the network (Fig. 4, and P2_1 in Fig. 5). In the low-temperature heating system, the design values for the supply and return temperatures were 75/35˚C on the primary side and 65/30˚C for the secondary side (Fig. 4). The system is capable of operating at a lower temperature level and with lower pump losses than the traditional DH network, since the adjustment is made via the speed-controlled pumps, not with traditional control valves [12], [15].

Fig. 3. Apartment buildings and the ring network in Kaarina, Finland [21].

In addition to the ring network connection, the renovation of old heat exchangers and automation as well as the utilization of an extract air heat pump were the starting points for improving energy efficiency. One common heat pump was selected for all buildings and was connected in parallel with district heating, i.e., both energy systems were heating the network. Heat recovery from the extract air was carried out along the collecting lines from all real estates to one point for a heat source of the heat pump. According to Fig. 4, placing the extract (exhaust) air heat pump into the heating system brings significant energy savings. In addition, the ring network coupled with mass flow control provides a good heat transfer efficiency when mass flows are equal on both sides of the heat exchanger [14]. The entire system, i.e., locations of water circuits, heat pump, line valve, nominal power of main heating and DHW heat exchangers, and dimensioning temperatures (supply and return) on the primary and secondary sides are illustrated in Fig. 4. In the current stages of research, the new type of control and network planning strategy has been applied (and principally described) for only the low-temperature DH network and space heating, not for the DHW circuit. Therefore, there are small contradictions regarding the DHW lines between Figs. 2, 3 and 4.

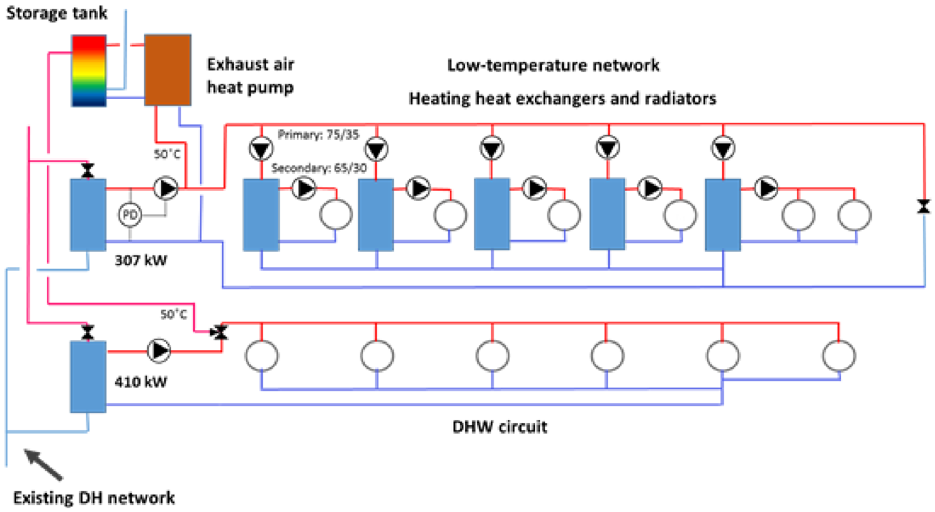

Fig. 4. Heating of the network and the domestic hot water circulation.

In the studied area heating system, additional heat is taken from the DH network when the heating power of the heat pump is insufficient (Fig. 4). The heat pump was heating the low-temperature network (with high-temperature DH), and it preheated the domestic hot water. In the DHW system there is a common heat exchanger (LS01) and pump (P1), as well as a conduit for six houses (Figs. 4 and 5). Traditionally house-mounted DHW heaters and pumps have been used.

The modification and construction works required to receive the low-temperature district heating system were completed in autumn of 2015. Preliminary data were collected, and piping and heat transfer planning and excavation works were completed in the winter of 2015. During the summer months, the focus was on installation works, pipes, heat exchangers, and heat pump installations. A new type of low-temperature grid was partly built using the old DH lines. The missing part was added so that the ring line was closed (Fig. 3). The heat recovery equipment of the extract air was carried out with brush heat exchangers and exhaust air fans, which could be installed in cramped attic rooms. The brush heat exchanger is highly efficient in heat recovery [22] as follows. Its contact area with the gas is large since the heat transfer surface consists of countless copper or aluminum wires. In the fluid side, efficient heat transfer is guaranteed by the spiral tube structure. There was no need to make changes above the roof, and the facade remained tidy.

3. Results

3.1 Starting the test plant and objective of the study

After the last installation work and preliminary adjustments, the plant was launched in October of 2015. It is noteworthy that the new network started faster than conventional systems. Initially, the area's line valves were completely open to show how well the system worked with just pump control. The overall pressure loss of the ring line was approximately 5 kPa at the initial stage. This is a remarkable result given the fact that the house-specific pressure drop (consumer equipment) should traditionally be set at 60 kPa in Finland [23]. In a traditional system, that pressure drop should be able to operate the control valve and overcome pressure loss of the heat exchanger [13]. In the new concept, the flow rate and pressure loss are smaller [12, 14]. The ring network has a unique feature compared to traditional networks: it equalizes the pressure differences of all consumers. That pressure difference is equal to the total pressure loss of the network. In addition, the mass flow control is based on a greater temperature difference (temperature cooling) in heat exchangers. Hence, DH flow rates are smaller. As a result, total pressure loss of the network is only a fraction of its traditional value. The design pressure drop value of the main heat exchanger for the area heating was approximately 10 kPa, and the heat exchanger design values of space heating in buildings were 3 kPa.

In the first phase, the pump control has been implemented in houses only for space heating (heating heat exchanger). In the following projects, the domestic hot water preparation will also be carried out by a pump (DHW heat exchanger). In the current study, the DHW system was realized based on existing technology with a common water circulation. In future DHW systems, an instantaneous low-temperature DH substation with DHW preparation by the primary water supply will be used [24]. In the pump-controlled system, the temperature cooling of the primary supply water is high, as is the heat exchanger effectiveness [14]. The objective of the research project was to produce, after design and construction, measurements of verified information on the effects of low-temperature DH on the energy efficiency of the area. Such research data makes it possible to evaluate the utilization of the heat concept more widely. A far-reaching goal is to show ways to improve the overall efficiency of DH systems.

3.2 Follow-up measurements and energy efficiency of the system

District heating measurements focus on mass flows, temperatures, and energy consumption. About half the thermal energy escapes the building in the form of heat loss by ventilation and the other half by conduction through walls, the floor, and the ceiling [14]. Sensors are constantly measuring the temperatures of the building's supply and return water, and temperature cooling refers to the difference in their temperatures. A large cooling is a sign of the correct adjustments and the functionality of the system.

The total energy consumption used to heat buildings does not change when the ring network and the extract air heat pump are deployed. Electricity consumption of circulating pumps used for heating the premises is low, which is still reduced by the introduction of speed-controlled pumps installed in the modification works. Consumption of DHW will also remain unchanged. The introduction of the extract air heat pump and the collector pumps increase the electricity consumption. The heat pump preheats the domestic hot water and generates warm water for space heating together with district heating (Fig. 4). This report does not separately specify the energy consumption of the DHW and space heating, nor the electricity consumption of other circulation pumps.

The Schneider Electric eValvomo internet program was used in the measurements (Figs. 5 and 6) [25]. It was able to monitor the cumulative heat energy consumption of buildings, the instantaneous heating power, and the thermal energy production, as well as the electric energy consumption of the heat pump (with the collection circuit pumps). The DH energy consumption is assumed to be as the difference between the total heat consumption of the houses and the heat produced by the heat pump, due to the deficiencies of the monitoring system. Hence, in the practical study, the thermal losses are assumed to be negligible in a low-temperature network. No more numerical data were able to be collected from the energy monitoring system. The follow-up measurements were accomplished during January 1 – December 29 (2016).

In winter and spring of 2016, temperatures in the low-temperature ring network (Fig. 3) remained fairly constant regardless of fluctuations in outdoor temperature, and the heat pump quite uniformly produced the rated power of 60 kW (59.4 kW, Fig. 5) as the heating water of temperature 48˚C (48.1°C) and the preheating of domestic hot water. The connection of the (existing) high-temperature district heating network with the low-temperature ring network and the heat pump in the area heating are presented in Figs. 4 and 5. Heating water comes from the heat pump and from the main heat exchanger LS02 (Fig. 5) by district heating for heating the premises. The heating water temperature is primed by the district heating.

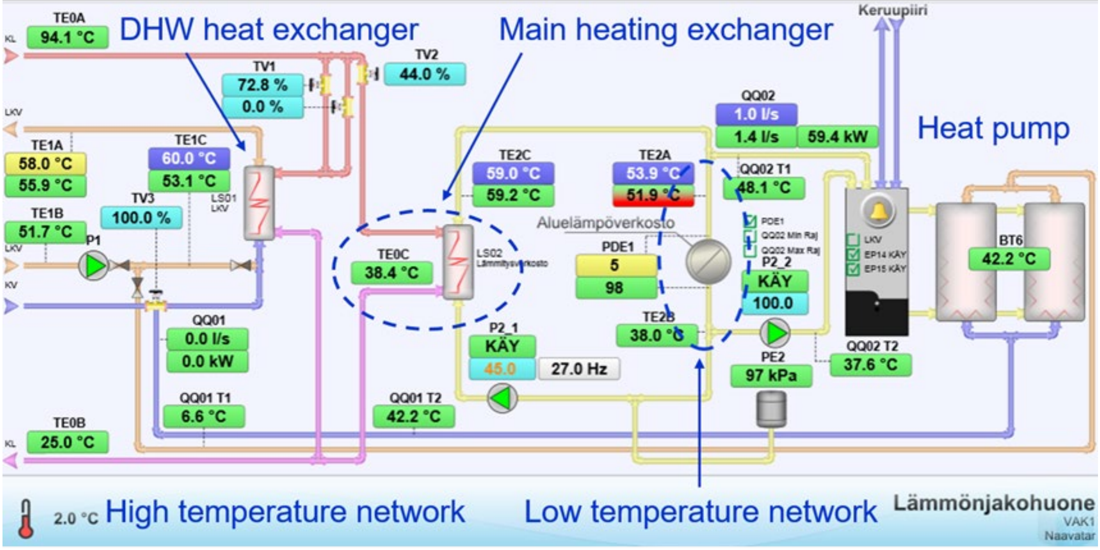

Fig. 5. Common heating station of buildings located in building Harmaa and connection of the high-temperature DH network with the low-temperature ring network, and the heat pump in the area heating (eValvomo March 23, 2016) [25], [26].

By the end of April 2016, the average coefficient of performance of the heat pump COP in spring was 3.99. District heating accounted for only 31% of the heating energy of buildings (DHW and space heating), and the rest was carried out by heat pump. It was also immediately apparent that heating of domestic hot water with the one common heat exchanger and pump worked as expected when they provided enough hot water for six buildings. [26] In the summer of 2016, the heat pump ran partially at night, providing water of approximately 30°C for the space heating. Normally, the DH system does not react to ambient temperature outside the heating season.

The most important task of the heat pump is to produce hot water evenly for the area heating, which is further heated by district heating if needed. In the autumn, the heat pump operation was more uneven. At times, the heat pump was off and the temperatures in the low-temperature DH network varied more during the day than in the spring. For these reasons, the share of district heat in the autumn was higher than in the spring. The temperature drop of the ventilation exhaust air varied between 8 °C and 13 °C on the monitoring moments in the brush heat exchangers. The corresponding temperature rise of the water/glycol solution was 3 °C-6 °C. The temperature of the solution in the collector circuit after the heat exchanger toward the heat pump (HP) varied between 6 °C and 14 °C. The higher heat source temperature increases the performance of the HP (COP), but decreases the amount of the heat recovered from the air. Heat recovered also depends on the used refrigerant.

Based on the follow-up measurements, the mass flow control for space heating works as expected when the equal mass flow rate is adjusted to both sides of the heat exchanger in the house heat distribution center. Fig. 6 shows the connection of houses “Valko 1 and 2” to the heating network. A heating heat exchanger of the house(s) and the speed-controlled pumps are located in the common heat distribution room (Figs. 3 and 6). The DHW is heated by the high-temperature DH. At the moment of observation, the frequencies of the primary and secondary side pumps were equal (65 Hz), as seen in Fig. 6; the mass flows and temperature differences in the heat exchangers were almost equal in the other load conditions as well [13]. According to the study, the mass flow control with speed-controlled pumps works also in refurbishment sites, such as in Vahakas properties, when the received temperature cooling (e.g., 46.1-35.0°C = 11.1°C) in the existing radiators may be smaller (Fig. 6). In general, this house-specific temperature difference (cooling) was smaller than received in earlier theoretical research steps.

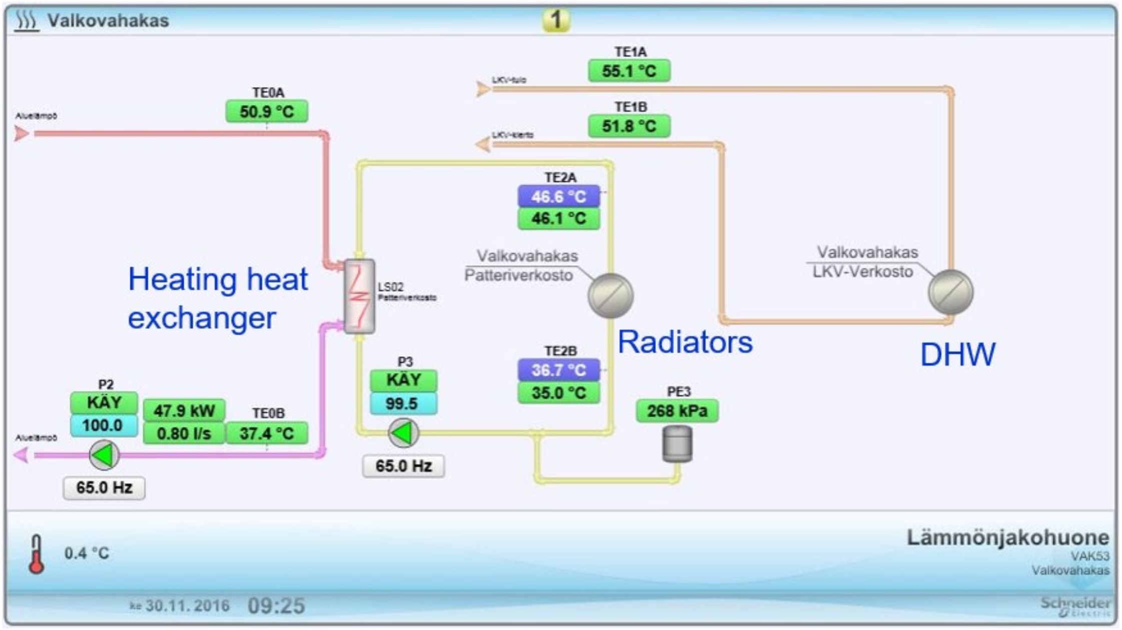

Fig. 6. Connection of houses “Valko 1 and 2” to the heating network (eValvomo November 30, 2016) [25].

The highest temperature cooling in the DH system (e.g., 94.1-25.0°C = 69.1°C) occurred in the main heating heat exchanger (LS02) in conjunction with the DHW heat exchanger (LS01) (Fig. 5). The highest temperature cooling was also received in the Vahakas case by adjusting a smaller flow rate to the primary side of LS02 compared to area heating (secondary) side, where the corresponding temperature difference was smaller, e.g., 59.2 °C- 38.0 °C = 21.2 °C, Fig. 5.

During the measurements, the incoming high-temperature DH water temperatures varied from 80°C to 116°C, and the return temperatures were between 18°C and 50°C. The return temperatures, less than 20 °C, sometimes occurred outside the heating season. The temperature received a value of close to 50 °C in the coldest season in January, when the temperature of the DH supply water was high. In the summer of 2016, the average return temperature was about 35 ˚C, with the DHW being heated. In the monitoring, it was found that the average return temperature toward the heating plant was close to the return temperature of the low-temperature area heating.

In the winter of 2016, the initial indicators of the new system were evaluated. The district heating system operated fairly evenly throughout the spring. The heat pump provided 50 °C water with a heating power of 60 kW (Fig. 5), which is the nominal output of the exhaust air heat pump. The efficiency of the heat pump COP at that time was about 4.5 [26].

The energy price for the DH was about 70 €/MWh (69.63 €/MWh) in 2016 in the Kaarina, Finland area. The total investment cost was €275 000, of which the share of the heat pump and realization of the ring network was €220 000. When making energy-efficiency measurements, one must turn to the energy producer to discuss the terms of the contract. In the profitability review with Turku Energy, the following figures were introduced as initial values: The prices of electricity and heat were estimated to be equal to €70 / MWh [13], [26]. Usually, the customer's order power (base charge) is checked after actions that improve the system's energy efficiency. With the energy provider, it was estimated that this would lead to around €5, 000 savings of the base charge based on the review periods of autumn 2015 and winter 2016. The initial back pay period was estimated to be nine years for the ring topology with the heat pump, replacement of the heat exchangers, etc. Carbon dioxide emissions were estimated to decrease by 62 tCO_2 annually [26].

Life Cycle Assessment (LCA) would allow for the impact evaluation of different processes and life cycle stages in the environment. Renewable sources of energy have less impact on the environment. Life Cycle Energy Analysis (LCEA) is an approach that accounts for all energy inputs into the building in its life cycle. The operation phase includes maintaining a comfort condition inside the buildings, water use, and powering appliances [27].

Next the energy efficiency was studied based on measurements. Fig. 7 shows the cumulative heat consumption figures for the Vahakas houses from the eValvomo program for the January 1–December 29 (2016) period. "Valko" consists of two buildings with a common heat distribution room (Fig. 3). Therefore, its heat consumption is higher than in other properties. Average heating per house was 95.46 MWh over the period considered.

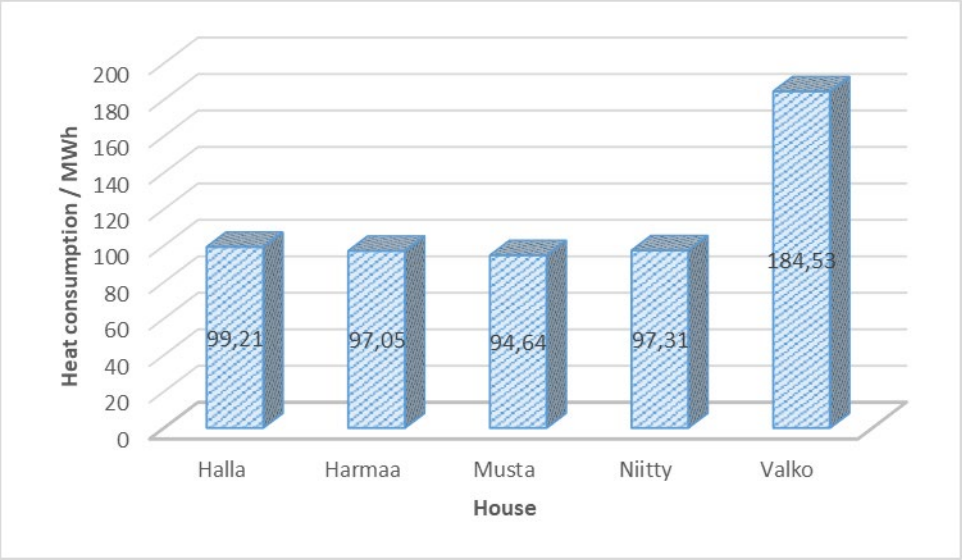

Fig. 7. Heat consumption of Vahakas houses.

Fig. 8 shows the total heat consumption of the houses, heating shares of exhaust air heat pump (HP), and district heating (DH).

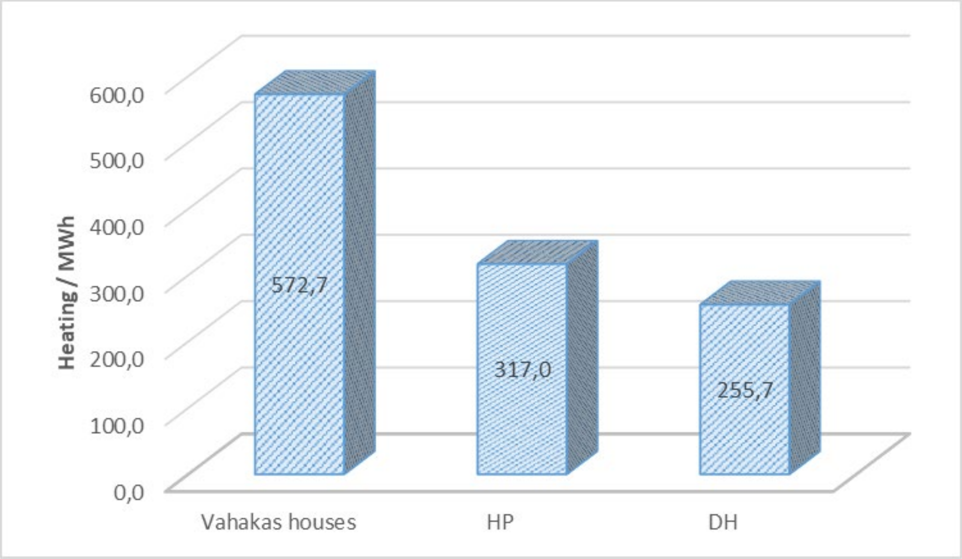

Fig. 8. Total heat consumption of the houses, heating shares of heat pump (HP), and district heating (DH).

On the basis of the measurements, the proportion of district heating was 45% and the coefficient of performance (COP) of the heat pump was 3.82. Table 1 shows verified energy efficiency indicators based on the measurements for the January 1–December 29 (2016) period.

Table 1. Indicators of energy efficiency based on the measurements.

The total cost estimate	€275 000
Energy savings of the period considered	317 MWh

Increase in electricity consumption	83 MWh
Savings: 22 190 € (energy) – 5 810 € (electricity)	€16 380
Change in district heating base charge (estimate)	€5 000
Payback period	12.9 Years
Coefficient of performance of the heat pump COP	3.82
Share of district heating (the rest of the heating with the heat pump)	45%
Reduction of CO2 emissions	40.7 tCO2

4. Discussion

By comparing the evaluation and the measurements, the energy savings by the heat pump for the 12-month period under review is 317 MWh (Fig. 8, Table 1). It is less than the estimation for the 10-month preliminary assessment (450 MWh) based on the steady operation of the heat pump in the spring of 2016. Since the heat pump (space heating at night) was operating alongside district heating (DHW production) in summer, it is relevant to also include the summer months in comparison. The payback period of the system was first estimated at approximately nine years. During the monitoring period, the actual heating savings in autumn of 2016 were less than estimated due to the hardware reliability: – the uneven operation of the heat pump and the lower heating demand. The heat pump did not operate at nominal power as in the spring. As a result, the payback period was about 12.9 years (Table 1). To ensure higher energy savings and a better payback time, more attention needs to be given to the smooth operation of the system during the heating season. However, the goal of the heat pump was to operate in nominal conditions. During heating season, it took thermal energy from exhaust air, which is almost the static room temperature of apartment buildings.

Comparing the performance of the present full-scale system to previous theoretical and small-scale experiments [12-15], the following conclusions were reached. The theoretical return temperature was lowest (close 20 °C) with the new technology compared to the traditional system [12]. In the current practical case, that temperature is close to 25 °C (Fig. 5). The most energy-efficient DH water supply temperatures in a case network were studied in [13]. If the ring network design was utilized, the DH system was easier to control. As a result, the total heat consumption within the heating season was lower compared to traditional systems [13] accounting for, e.g., heat losses in pipes. Theoretically expected and experimentally obtained heat loads were compared in [14] in the context of the simulation of a laboratory-scale test facility in the most common outdoor temperatures. In general, the obtained values were fairly close to the expected ones, which reinforced the validity of the experiments [14]. In the full-scale experiment, the correct operation of the network and heating of houses was realized. In the combined simulation of the theoretic DH network, heat losses of houses and the heat exchangers in the selected autumn and winter days, the pressure losses with mass flow control were only a fraction of their traditional values in heat exchangers [15]. This revealed at the beginning of the full-scale system. The general goal of the heat distribution concept has been to receive greater (than traditional) temperature cooling in area heating. This expected when adjusting equal temperature differences on the primary and secondary sides of the main and house specific heat exchangers. In Kaarina case, this temperature difference was higher than expected in the main heating heat exchanger (Fig. 5) but lower in existing radiators (Fig. 6). Since no numerical data were able to be collected from the energy monitoring system except for the heat energy consumption of buildings, in this complementary study, it was not easy to quantify the differences between the theoretical/small-scale experiments and the full-scale system.

Network energy losses can be reduced through the reduced pumping power demand and the reduced return temperature.

Taking into account the suitability of the used energy monitoring system (eValvomo) for the follow-up measurements, the study shows that the quantitative energy savings of houses came from the use of the extract air heat pump. The correct functioning of the ring network and the mass flow control were qualitatively proven [15], [26]. The frequencies of the pumps and the temperature differences on the primary and the secondary sides of the house-specific heat exchangers were equal in many cases. The average return temperature toward the heating plant was close to the return temperature of the low-temperature area heating. In earlier steps of the new DH technology realization, a heat pump was not included in the DH system. In the current case, it was installed with the new concept, as a novelty of research, to improve the energy efficiency as well. Thus, the role of the ring network and mass flow control became able to heat the buildings. In other words, the new system worked as expected.

5. Conclusions

The district heating system based on the ring network and the mass flow control concept was constructed and monitored in an existing heating system of apartment buildings in Kaarina, Finland. Renewal of old heat exchangers and automation, as well as the utilization of waste energy, were the starting points for the improvement of building renovation and energy efficiency. The extract air heat pump was connected in parallel to the low-temperature area heating. The share of district heating was taken from the high-temperature district heating network to the area. One common heat pump was selected for all properties to make the payback period as short as possible. At earlier stages, the concept of the ring network and mass flow control were studied by the authors. Now the extract air heat pump is connected to the system, which is a slightly different case. In the new heating system, additional heat is taken from the district heating network when the heating power of the heat pump is insufficient. Domestic hot water was produced with high-temperature district heating.

District heating measurements focus on mass flows, temperatures, and energy consumption. In spring of 2016, the heat pump evenly produced heat at a design power. In the autumn of 2016, the need for heating was lower, and the heat pump did not operate equally at the nominal power. Furthermore, the monitoring was also done for the implementation of the DHW production with only one heat exchanger and pump, which produced enough hot water for real estates.

The construction of the ring topology and the mass flow control (control valves replaced by the speed-controlled pumps) in heating of a block of flats was successful. When accounting for the suitability of the used energy monitoring system for the measurements, the study qualitatively shows the right functioning of the novel district heating concept. The circulating energy in the low-temperature network was efficiently recovered by the house-specific pumps and heating heat exchangers. The frequencies of the pumps and the temperature differences on the primary and secondary sides of the heat exchangers were equal. However, the temperature cooling in existing radiator circuits was small. The return temperature toward the heating plant was close to the return temperature of the area heating.

The quantitative energy savings were achieved through the extract air heat pump. The common exhaust air heat pump for six houses brings significant energy savings. The share of district heating was 45% during the monitoring period, and most of the heating energy (55%) was generated by a heat pump. This project shifted from traditional network design to the use of a completely new technology concept. The main result of the study is the practical construction of a low-temperature district heating system with the new type of control and network planning strategy for the first time in practice.

Acknowledgments

This study is supported by the Ministry of Employment and the Economy of Finland (TEM) and the ERDF-funded project, "Developing of bioeconomy collaboration and operating environment in Kymenlaakso – KYMBIO." Thanks are also given to the companies participating in the project. The ring network was jointly implemented with Real Estate Kaarina rental houses, Turku Energy, Schneider Electric, Alfa Laval, Kolmeks, Kaukora, Hydrocell, Energy Management Tapio Mäkilä, and Aalto University.

References

[1] S. Werner, International review of district heating and cooling, Energy, Vol. 137, pp. 617-631, 2017.

[2] A. Lake, B. Rezaie, S. Beyerlein, Review of district heating and cooling systems for a sustainable future, Renewable and Sustainable Energy Reviews, Vol. 67, pp. 417-425, 2017.

[3] S. Werner, The position of district heating in the world and the corresponding use of renewables, Solar World Congress of International Solar Energy Society, Paper S2.1, Göteborg, 2003.

[4] S. Werner, District heating and cooling, Encyclopedia of Energy, Cleveland CJ, Elsevier, pp. 841-848, New York, 2004.

[5] S. Frederiksen, S. Werner, District heating and cooling, Lund Studentlitteratur, 2013.

[6] K. Comakli, B. Yüksel, Ö. Comakli, Evaluation of energy and exergy losses in district heating network, Applied Thermal Engineering, Vol. 24 (7), pp. 1009-1017, 2004.

[7] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, et al., 4th generation district heating (4 GDH): integrating smart thermal grids into future sustainable energy systems, Energy, Vol. 68, pp. 1-11, 2014.

[8] D. S. Østergaard, S. Svendsen, Replacing critical radiators to increase the potential to use low-temperature district heating – a case study of 4 Danish single-family houses from 1930s, Energy, Vol. 110, pp. 75-84, 2016.

[9] D. Schmidt, A. Kallert, M. Blesl, S. Svendsen, H. Li, N. Nord, K. Sipilä, Low temperature district heating for future energy systems, Energy Procedia, Vol. 116, pp. 26-38, 2017.

[10] M. Brand, S. Svendsen, Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment, Energy, Vol. 62, pp. 311-319, 2013.

[11] L. Gustavsson, A. Dodoo, N. I. Truong, I. Danielski, Primary energy implications of end-use energy efficiency measures in district heated buildings, Energy and Buildings, Vol. 43 (1), pp. 38-48, 2011.

[12] M. Kuosa, K. Kontu, T. Mäkilä, M. Lampinen, R. Lahdelma, Static study of traditional and ring networks and the use of mass flow control in district heating applications, Applied Thermal Engineering, Vol. 54, pp. 450-459, 2013.

[13] T. Laajalehto, M. Kuosa, T. Mäkilä, M. Lampinen, R. Lahdelma, Energy efficiency improvements utilising mass flow control and a ring topology in a district heating network, Applied Thermal Engineering, Vol. 69, pp. 86-95, 2014.

[14] M. Kuosa, M. Aalto, M. El Haj Assad, T. Mäkilä, M. Lampinen, R. Lahdelma, Study of a district heating system with the ring network technology and plate heat exchangers in a consumer substation, Energy and Buildings, Vol. 80, pp. 276-289, 2014.

[15] J. Iturralde, M. Kuosa, T. Mäkilä, M. Lampinen, R. Lahdelma, Heat exchanger measurements in a mass flow controlled consumer substation connected to a ring network, Applied Thermal Engineering, Vol. 90, pp. 733-741, 2015.

[16] Future low temperature district heating design guide book, Final Report of IEA DHC Annex TS1, Low Temperature District Heating for Future Energy Systems, Edited by Dietrich Schmidt and Anna Kallert, Published by: A GFW-Project Company, Frankfurt am Main, Germany, 2017.

[17] H. Hämäläinen, Improvement of cooling with the new connection and adjustment solutions of district heating, Master's Thesis (in Finnish), Helsinki University of Technology, Finland, 2000.

[18] H. Nuora, Mass flow control – power control of closed piping system by changing pump's speed of rotation, Master's Thesis (in Finnish), Aalto University, School of Science and Technology, Espoo, Finland, 2011.

[19] T. Laajalehto, Energy efficiency analysis of mass flow control and ring topology in district heating network, Master's Thesis (in Finnish), Aalto University, Espoo, Finland, 2013.

[20] T. Laajalehto, M. Kuosa, M. Lampinen, R. Lahdelma, Energy efficiency improvements utilising mass flow control and a ring topology in a district heating network, ECOS 2013: The 26th International Conference on Efficiency, Cost, Optimization and Environmental Impact of Energy Systems, Guilin, China, July 16-19, 2013.

[21] https://earth-fi.com/?gclid=EAIaIQobChMI-IHPvvyM3QIVA6QYCh2Z8wrMEAAYASAAEgKdSPD_BwE (address selected to links address space: Taksvärkkikuja, 20780 Kaarina, Finland).

[22] hydrocell.fi/en/heat-recovery

[23] District heating handbook, (in Finnish), Finnish Energy (association), 2006.

[24] M. Brand, J.E. Thorsen, S. Svendsen, Numerical modelling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of DHW with respect to service pipes, Energy 41 (2012) 392-400.

[25] Schneider Electric eValvomo, Available at: https://www.evalvomo.fi.

[26] I. Mäkelä, New district heating networks and their measurements, Bachelor's Thesis (in Finnish), Aalto University, Espoo, Finland, 2016.

[27] T. Ramesh, R. Prakash, K. K. Shukla, Life cycle energy analysis of buildings: An overview, Energy and Buildings 42 (2010) 1592-1600.