International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: #487

ANALYSIS OF DISTRICT HEATING SYSTEMS INTEGRATING DISTRIBUTED SOURCES

Mohammad Shakerin[1], Natasa Nord[1*]

1 Department of Energy and Process Technology, Norwegian University of Science and Technology (NTNU), Kolbørn Hejes vei 1B, Trondheim 7491, Norway

ABSTRACT

District heating (DH) systems play an important role in increasing the share of renewable energy utilization. In this study, the operation of the still new concept of a prosumer in a DH system by means of mathematical modelling was analysed. The DH ring of a university campus was investigated to find out the consequences of datacenter waste heat energy exploitation on the operation of DH. Based on fundamental equations from continuum mechanics, the hydraulic and thermal parts of the system were modelled and developed in MATLAB. The scenarios for network performance improvement were introduced and investigated. The result showed that integrating waste heat to DH grids might cause pressure imbalance in substations located close to the prosumer. Variable speed pump control together with valve flow control was found as an alternative solution to solve this issue. Lowering temperature levels in the DH grid led to heat energy saving in distribution pipes, while reduced annual waste heat recycling. Despite the assumptions and simplifications applied, the result indicated the main features, advantages, and disadvantages of integration of a prosumer to DH grids.

Keywords: Low-temperature district heating, Prosumer, Distributed energy sources, Renewable energy sources

NOMENCLATURE

Symbols

μ	Viscous friction coefficient
β_k	Local loss coefficient
L	Pipe length (m)
D	Pipe Diameter (m)
ρ	Density (kg/m^3)
v	Velocity (m/s)
S	Pipe cross section area (m^2)
c_p	Specific heat (kJ/kg.K)
Ω	Pipe Cross section perimeter (m)
U	Heat transfer coefficient (W/m^2)
t	Time (s)
T	Temperature (K)
p	Pressure (Pa)

1. INTRODUCTION

District heating (DH) systems play a determinative role regarding the prospect of energy systems by offering flexibility to the integration of renewable energies through synergies between waste-to-energy processes [1-3]. Recent studies on the state of DH in future energy systems are mainly focused on issues associated with connection of renewables and DH [4-7], introduction of prosumers to the existing and future DH [8], design approaches that enable treating bidirectional flow in network, and simulation methods that reflect operation aspects of utilizing renewables in DH [7, 9-12]. The most attractive for energy companies are big energy exporters that may become prosumers with high temperature levels like waste heat from datacenters [13]. A growing number of datacenters gives incentives to utilize this excess heat in nearby facilities and DH fits perfectly for this objective. However, barriers such as relatively low export temperatures that do not fit in high temperature DH grids and the difficulty in heat logistics are yet to be sustainably tackled.

Prosumers that are using and delivering heat at the same time are associated with intermittent energy generation, which questions them as a reliable heat provider. Temperature oscillations in the network could take place and change in differential pressure is inevitable [9, 10]. Transition to renewable energy society requires an in-depth understanding of the effect of prosumers on pressure and temperature levels at each point of a DH network. This study aimed to understand the impacts of the introduction of prosumers in the DH system. As a case study, the existing DH ring at a university campus in Trondheim, Norway, was modelled in detail in order to analyze the technical parameters in presence of a heat exporting datacenter as distributed auxiliary heat producer.

2. THEORY AND METHODS

The operation of DH as a complex thermo-fluid interacting system may be analyzed once the state properties are properly found in each pipe-section of the network. Hypothesizes from continuum mechanics allows developing mathematical models for treating isothermal and non-isothermal properties of the system via momentum, continuity, and energy equations [12]. Graph theory [12, 14] mathematically expresses the interconnection of nodes (junctions) and branches (pipe-sections) of a DH system by means of an incidence matrix and enables the definition of pressure and temperature at each node while defining fluid velocities through each branch.

2.1 Fluid dynamic model

One dimensional steady state momentum equation for j^{th} branch of pipe section between two junctions and mass conservation at i^{th} the junction was derived as:

$$(p_{out} - p_{in}) = -\frac{1}{2}\mu\frac{L}{D}\rho(v)^2 - \frac{1}{2}\sum_k \beta_k\,\rho(v)^2 + \Delta p_{PUMP} \quad (1)$$

$$\sum_j \rho_j v_j S_j + G_{ext} = 0 \quad (2)$$

G_{ext} is mass the flow rate that is either ejected or injected through the node. Hydraulic losses were accounted as Darcy Weisbach notion of pipe-flow resistance and local losses at junctions. Due to the dependency of hydraulic losses to velocity, the non-linear momentum equation is not analytically solvable. Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) was chosen as a commonly used iterative solution method for treating nonlinear Navier-Stokes equations with an acceptable degree of accuracy [12, 15, 16].

2.2 Thermal model

One dimensional energy conservation low when neglecting conduction heat transfer around i^{th} junction including half of each connecting branch may be written as:

$$\frac{(\rho_j c_{p,i} T_i)^t - (\rho_j c_{p,i} T_i)^{t-\Delta t}}{\Delta t}\left(\sum_j \frac{S_j L_j}{2}\right) + \sum_j \rho_j^t v_j^t S_j^t T_j^t {c_{p,j}}^t = -\sum_j \frac{L_j}{2}\Omega_j U_j\left(T_i^t - T_{\mathrm{Sur}}\right) \quad (3)$$

The energy equation is discretized in time by Euler backward method. T_j is the temperature at the boundary of control volume surrounding node. An upwind scheme translates the temperatures at the boundary to the node in upstream. Heat transfer to surrounding through the walls is perpendicular to the assumed direction. Therefore, the heat exchange was considered as a volumetric sink term.

Sub-models of pumps, heat users, and a prosumer substation were developed and integrated into the main model and developed in MATLAB. The main parameters this study aimed to analyze were the temperature and pressure levels in each junction and mass flow rates in each pipe section of the selected network.

3. CASE STUDY

The DH ring at the university campus shown in Fig 1 supplied heating to 24 buildings from the main DH of Trondheim, while a datacenter facility as a prosumer building exports heating to the return line of the university DH ring.

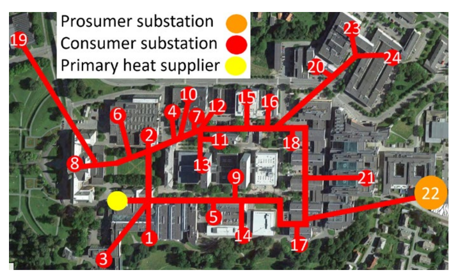

Fig 1 Layout Gløshaugen campus DH

This prosumer connection was made because of the high supply temperature that was used in the main DH. For investigating the possible solutions of integrating waste heat, the existing interface configuration, return to return (R2R), was tested against an alternative setup called return to supply (R2S).

Real performance data of the heat pump in the prosumer substation revealed the increase in the compressor electricity use when the return temperature of the DH ring increased while the cooling load of the datacenter slightly decreased. The compressor power of the heat pump was defined as a function of the return temperature in the DH ring at the campus. The amount of the recovered heat from the waste heat source was the sum of cooling load and compressor power.

In this study, three assumptions were made about the use of waste heat and they are summarized in Table 1. Cooling process in the datacenter made the waste heat almost always available at a constant level during the year with an average rate of 1 MW for each 600 kW cooling load.

Table 1 Mass flow rate share of reheating water

	(kg/s)	(%)	
		R2R	R2S
Case 1	10.2	9.5	10.5
Case 2	12.7	11.8	13.4
Case 3	15.5	14.4	16.9

In the current DH ring, see Fig 1, only one circulation pump operated with constant speed to circulate the water. The head of the circulation pump was adjusted in order to meet the pressure requirements of the building substations. The substations included a heat exchanger and a flow control valve with pressure drops proportional to the square of mass flow rate and variable valve capacity adjusted by the opening position of the valve. To ensure the performance of the heat exchangers at the building substations, the minimum pressure drop required at the furthermost substation was set to 0.7 bar. The *differential pressure control scenario (PC)* tried to maintain a constant pressure level of 3 bar between the supply and the return line using variable speed control. A sensor at the farthest consumer substation uses the inputs of pressure supplied from the pump, pressure drop within the supply line and pressure of supplied waste heat in order to adjusts the valve opening position for the desired hydraulic balance.

The *outdoor temperature compensation scenario (OTC)* controlled the DH supply temperature based on the outdoor temperature. According to the university energy monitoring platform, the supply temperature was suggested as a linear function of the outdoor temperature ranging from 90°C to 55°C.

4. RESULT AND DISCUSSION

Fig 2 shows that the minimum pressure drop in a consumer substation near waste heat source dropped below the limit of 0.7 bar during certain hours of the year for the reference scenario with the R2R connection. This failure occurred more frequently when waste heat injection increased and during the months with low heating demand. This happened due to the lower flow rate in the network that made the pressure from datacenter to disturb the hydraulic balance of nearby buildings. This problem was avoided with the PC scenario and did not appear in the R2S connection. In PC scenario the DH network experienced lower pressure levels, while the adverse effect of the pressure from waste heat source on its nearby substations was less observed. The R2S connection helped to increase the supply pressure, while not compromising the hydraulic requirements of the building substations.

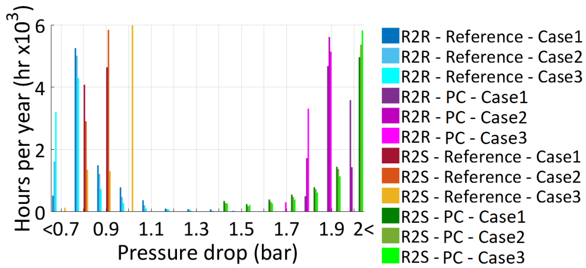

Fig 2 Pressure gradient at a consumer substation

Annual energy performance of the prosumer in Fig 3 shows higher heat production for the reference scenario with constant supply temperature comparing to the OTC. Increased amount of the waste heat source in both scenarios contributed to higher annual heat share from the waste heat source. Thermal energy losses in Fig 4 were found lower when the share of waste heat was increased and when the OTC was adopted. The R2S connection showed better results for limiting heat losses of the DH grid.

Annual energy use of the compressor of the heat pump and the circulation pump in the DH grid is shown in Fig 5 and Fig 6. In the OTC scenario temperature levels were lower and therefore the compressor in the heat pump system worked with lower pressure ratio. Higher waste heat production in the reference scenario was accompanied by higher compressor electricity use.

In the R2S connection for Case1 to Case3, the dependency of heat supply on the waste heat source gradually increased and therefore the circulation pump required relatively less input power. However, the R2R connection was not affected by a change in the operation of the waste heat source. Adopting the PC scenario for the circulation pump control considerably prevented excessive energy use of the circulation pump by reducing the supply pressure levels while the variable capacity flow control valve damped the waste heat overpressure.

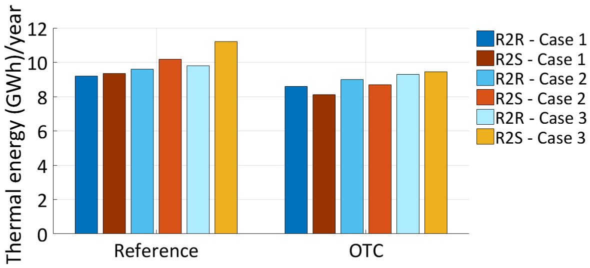

Fig 3 Annual renewable waste heat production

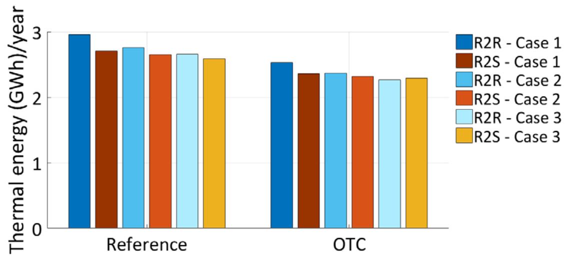

Fig 4 Annual thermal energy loss

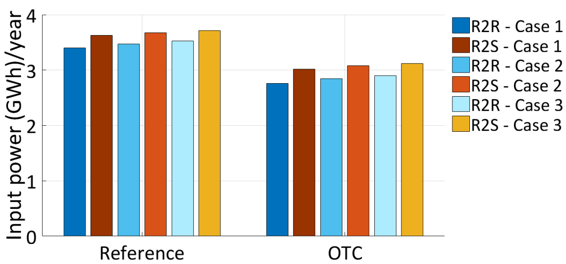

Fig 5 Annual compressor electricity use

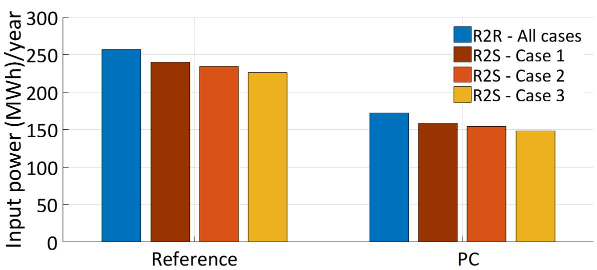

Fig 6 Annual circulation pump electricity use

5. CONCLUSIONS

The study identified that recycling heat from the local heat prosumer had both advantages and limitations. The prosumer as a secondary energy source produced its own pressure cone in the system. It had a negative effect on differential pressure of the nearby customer substation and scaled up when the share of recycled waste heat to the DH system increased. Adopting the variable speed control for the pumping system together with valve control in consumer substations resulted in energy saving. Further, it helped to control pressure cones of the prosumer, specifically when heat demand of the network was low and effect of the prosumer was more significant in nearby nodes.

For the OTC scenario, it was found that the reduction in both distribution thermal losses and the heat pump energy use were the most important economic advantages. However, lower temperature levels resulted in less waste heat recovery. A higher share of circulating water in the datacenter substation caused a reduction of water temperature introduced by the waste heat source.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support from the Research Council of Norway through the research project Understanding behavior of district heating systems integrating distributed sources under FRIPRO/FRINATEK program.

REFERENCE

[1] Union I. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Bryssel, 2014.

[2] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy. 2010;35(3):1381-90.

[3] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy. 2017;137:556-65.

[4] Nord N, Schmidt D, Kallert A, Svendsen S. Improved Interfaces for Enabeling Integration of Low Temperature and Distributed Heat Sources–Requirements and Examples. 2016.

[5] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy. 2015;145:139-54.

[6] Averfalk H, Werner S. Essential improvements in future district heating systems. Energy Procedia. 2017;116:217-25.

[7] Duquette J, Rowe A, Wild P. Thermal performance of a steady state physical pipe model for simulating district heating grids with variable flow. Applied energy. 2016;178:383-93.

[8] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy. 2014;68:1-11.

[9] Ancona M, Branchini L, De Pascale A, Melino F. Smart District Heating: Distributed Generation Systems' Effects on the Network. Energy Procedia. 2015;75:1208-13.

[10] Brand L, Calvén A, Englund J, Landersjö H, Lauenburg P. Smart district heating networks–A

simulation study of prosumers' impact on technical parameters in distribution networks. Applied Energy. 2014;129:39-48.
[12] Sciacovelli A, Verda V, Borchiellini R. Numerical design of thermal systems. Clut, Torino. 2013.
[13] Wahlroos M, Pärssinen M, Manner J, Syri S. Utilizing data center waste heat in district heating–Impacts on energy efficiency and prospects for low-temperature district heating networks. Energy. 2017;140:1228-38.
[14] Unternährer J, Moret S, Joost S, Maréchal F. Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy. Applied energy. 2017;190:749-63.
[15] Khawaja H, Moatamedi M. Semi-Implicit Method for Pressure-Linked Equations (SIMPLE)–solution in MATLAB®. International Journal of Multiphisics. Volum 12. 2018.
[16] Quarteroni A, Saleri F, Sacco R. Numerical mathematics. 2007.