ISSN 2004-2965 Energy Proceedings, Vol. 23, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 2, 2021, Thailand / Virtual
Paper ID: 590

Modelling of Electrical – Thermal - Hydraulic System Interdependencies in 5th Generation District Heating and Cooling Networks

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ABSTRACT

This work presents a method for steady state modelling and simulation of 5th Generation District Heating and Cooling (5GDHC) Networks. The method allows to characterise interdependencies between electrical, thermal, and hydraulic parameters for different 5GDHC network configurations. Two case studies, one with free floating network temperature, and the second with active network temperature control are demonstrated. Simulation results show that the electrical power consumption of Water Source Heat Pumps (WSHP) at demand substations are highly sensitive to the balance of heating and cooling loads when the network is operated with free-floating temperatures. In both cases, it was shown that the total electrical power consumption of the network is minimised when the heat injection and extraction applied by the WSHPs is balanced.

Keywords: 5th generation district heating and cooling, heat network, smart grid, cooling network, heat pump

1. INTRODUCTION

District Heating and Cooling (DHC) networks have an important role to play in increasing energy efficiency and reducing carbon dioxide emissions from energy supply in urban centres [1, 2].

A District Heating (DH) or District Cooling (DC) network comprises a network of pipes connecting buildings, through which a heat/cold carrier medium (usually water) is distributed. The evolution of district heat technology is reported in stages of:

- 1st generation (1GDH) to 3rd generation (3GDH) focused on reduction of distribution temperatures and increased integration of CHP generators and waste heat, to increase efficiency and reduce primary energy demand [3-5].
- The 4th generation (4GDHC) facilitated parallel operation of heating and cooling networks, further reduction of distribution temperatures, and further integration of waste and renewable heat. It also introduced the smart grids concept where suppliers, consumers, and the network communicate and co-ordinate to improve efficiency and reliability and reduce peak demand [4, 6].

High-temperature networks (1-3GDH) suffer from significant heat losses, especially in summer when systems typically operate only to meet hot water demand, causing high retention time of water in the network. Low temperature systems (4-5GDHC) can reach higher efficiencies by operating at low temperatures, however, in 4GDHC systems the same pipelines are not able to simultaneously provide both heating and cooling services to different buildings and therefore enable heat sharing at the individual building level. 5GDHC technology represents a further step in DHC technology by permitting [7, 8] :

- Recovery of low temperature excess heat at the individual building level.
- Simultaneous provision of heating and cooling services with the same pipelines, independent of the network temperature, due to bi-directionality and integration of WSHPs at all substations.
- Increased coupling with electricity grids which could provide flexibility when heat storage is deployed.
- Negligible thermal losses in the network.

2. 5TH GENERATION DISTRICT HEATING AND COOLING NETWORKS

5GDHC networks are at the early stage of development, but several systems are already in operation in Europe, mainly started as pilot projects [8]. It is possible that a concise and unambiguous definition of 5GDHC technology is not yet widely agreed, with "Low

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

Temperature", "Cold", and "Neutral Temperature" district heating systems having many characteristics that are similar to that of 5GDHC. A definition for 5GDHC which distinguishes it from other low temperature systems is proposed:

"5GDHC is a thermal energy supply network using water, water-glycol, or brine as a thermal carrier medium, supplying substations with reversible WSHPs to provide heating or cooling services to buildings with the same pipelines, independent of the network temperature. The network temperature is close to the ground temperature, such that thermal losses are negligible. The low network temperature allows direct exploitation of industrial and urban waste heat and renewable heat sources at low thermal exergy but is not usable for direct heating."

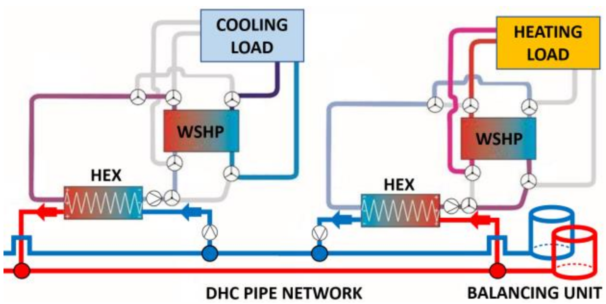

Fig. 1. 5GDHC Network

The 5GDHC pipe network supplies the thermal carrier medium at a temperature in the range of approximately 0-30°C to substations which are equipped with a heat exchanger (HEX), reversible WSHP, and a water circulation pump (fig. 1.). This combination allows substations to operate in heating or cooling mode independently of the network temperature:

- In heating mode, water is pumped from the hot pipe into the WSHP, heat is extracted from the water and injected into the building, and the cooled water is ejected into the cold pipe.
- In cooling mode, water is pumped from the cold pipe into the WSHP, heat is extracted from the building and injected into the water, and the heated water is ejected into the hot pipe.

Generally, if the aggregate heating load exceeds the cooling load on the network (heating-dominated), the temperature of the hot pipe will fall and the overall mass flow of the water in the network will be from the hot pipe into the cold pipe. The balancing unit must circulate water from the cold pipe into the hot pipe to balance the network. If the recirculated water is heated before injection into the hot pipe, the temperature of the hot pipe may be actively controlled. If the recirculated water is not heated, then the pipe temperature is not actively controlled and is referred to as "free floating". If the network is cooling-dominated, the opposite is true; the balancing unit circulates water from the hot pipe into the cold pipe, and the cold pipe temperature may be actively controlled by cooling the recirculated flow or allowed to float.

The hot and cold pipe temperature and mass flow balance are dependent on the Coefficient of Performance (COP) of the WSHP and the outlet temperature at each substation. The control of water flow in the network may be achieved by co-ordination of the distributed substation water pumps, or a combination of distributed substation and centralised balancing unit water pumps. 5GDHC moves away from a supplier centric model where the network operator ensures the central pumps maintain differential pressure and the correct supply temperature, to a prosumer model where individual users may exchange energy quantities (share heat). 5GDHC technology permits the exploitation of theoretically unlimited centralised and distributed heat sources.

3. METHOD FOR SIMULATION OF 5GDHCN

The key components of a 5GDHCN were modelled mathematically in a MATLAB based simulation framework for studying its steady-state operation characteristics. The key elements studied are:

- Electrical and thermal parameters of the water WSHP at consumer substations (COP, electrical power consumption).
- Hydraulic parameters (pressure, mass flow rate) of the 5GDHCN when supplying thermal loads.
- Thermal parameters (temperature at nodes, heat losses) of the 5GDHCN when supplying thermal loads.

Mathematical models to characterise the hydraulic and thermal behaviour of the network and the heat pump operation were combined to simulate the 5GDHC network.

The heat pump model calculates the COP, electrical power, and thermal power according to the heating or cooling load per substation and hot and cold node temperatures. The values are passed to the hydraulic model which determines the required substation node flow rates and calculates the pipe and node flow rates based on the pipe geometry and network topology. The values are passed to the thermal model which calculates the node temperatures based on the substation outlet temperatures, pipe heat loss parameters and network topology. The non-linear set of equations are solved using an iterative solution method. A modelling process flow diagram is in the appendix.

4. CASE STUDY

A test network consisting of two substations, one balancing unit, and three hot and three cold pipes with one hydraulic loop in the pipe network is shown in fig. 2. The hot and cold water carrying pipes layout is assumed to be symmetrical with water flow direction reversed. A full description of the input and output parameters are shown in in the appendix (table 1.).

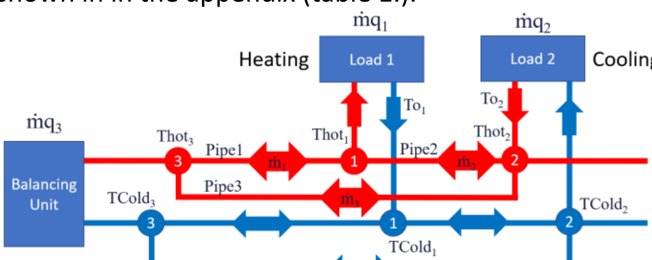

Fig. 2. 5GDHC Case Study Network

Load 1 (substation 1) operates in heating mode, supplying hot water to the consumer at 50 °C. Load 2 (substation 2) operates in cooling mode, supplying chilled water to the consumer at 7 °C. The outlet temperature of water from Load 1 is 10 °C and 30 °C at Load 2. The circulation pump of the mass flow dominant substation is specified to provide the required pump head to drive flow through both loads and the balancing unit. The water flow in the pipe network can change direction depending on the balance of the heating and cooling loads. In the simulations, the heating and cooling loads are varied so that the 5GDHC network operating point varies between a heating-dominated scenario and a cooling-dominated scenario.

A) Case Study One – Free Floating Temperature

There is no active control of the hot or cold pipeline temperature at the balancing unit. Water is recirculated at the balancing unit without any heat transfer. The average ambient ground temperature is assumed to be constant.

B) Case Study Two – Active Temperature Control

Active control of either the hot or cold pipeline temperature: When water is circulated from the cold pipe into the hot pipe (heat-dominant mode), the flow is heated to 30°C before injection at hot node 3. If water is circulated from the hot pipe into the cold pipe (cooling-dominant mode), the flow is cooled to 10°C before injection at cold node 3. Heating or cooling at the balancing unit is provided by an Air Source Heat Pump (ASHP), operating at an average summer ambient air temperature for the cooling dominated scenario, and an average winter ambient air temperature for the heating dominated scenario. The average ambient ground temperature is assumed to be constant.

5. RESULTS AND DISCUSSION

Fig.3. shows the node temperatures for Case Study One.

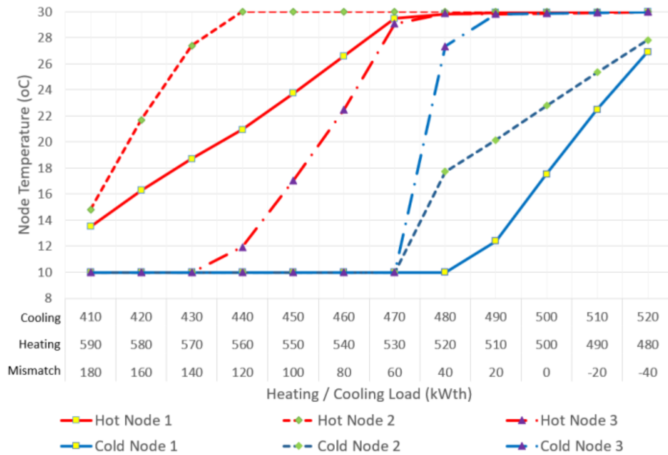

Fig. 3. Node Temperature – Free Floating 5GDHCN

As the network becomes more heating-dominated, the cold pipeline temperature reaches a minimum, and the hot pipeline temperature drops towards the cold pipeline temperature. As the network becomes more cooling-dominated, the hot pipeline temperature reaches a maximum, and the cold pipeline temperature is pulled up towards the hot pipeline temperature. When the hot and cold pipeline temperatures are close to convergence, the network is no longer able to balance.

Fig. 5. shows the COP, electrical power, and balancing mass flow for Case Study 2.

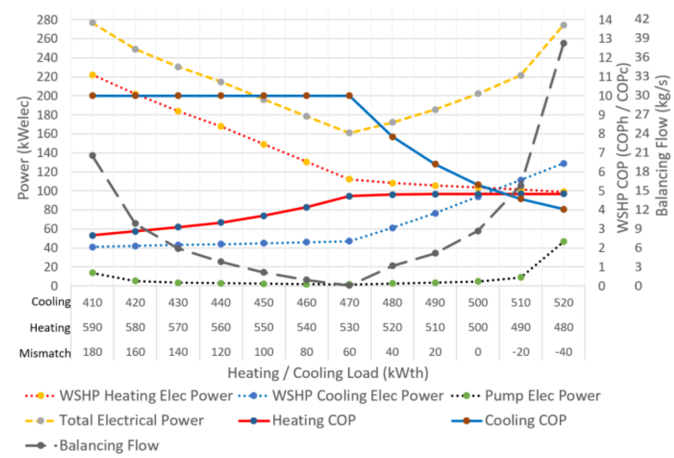

Fig. 5. Power/COP/Mass Flow – Free Floating 5GDHCN

The optimal operating point in terms of electrical power consumption is achieved when the network is heating-dominated by a magnitude of 60kWth. If the operating point moves further towards the heating-dominated region, at substation 1 the COP of the WSHP falls, and the mass flow rate increases to meet the thermal energy demand. If the operating point moves further towards the cooling-dominated region, at substation 2 the COP of the WSHP falls, and the mass flow rate increases to meet the demand. In both cases this increases the electrical power demand of the WSHP and circulation pump. It should be noted that the mass flow rate increases exponentially when moving away from the optimal operating point. This is because the reduction in WSHP COP coincides with increased thermal demand.

Fig. 6. shows the COP, electrical power, thermal power, and balancing mass flow for Case Study 2. The node temperatures are not shown as they remain relatively constant between heating-dominated and cooling-dominated scenarios because the balancing unit acts to stabilise the temperature.

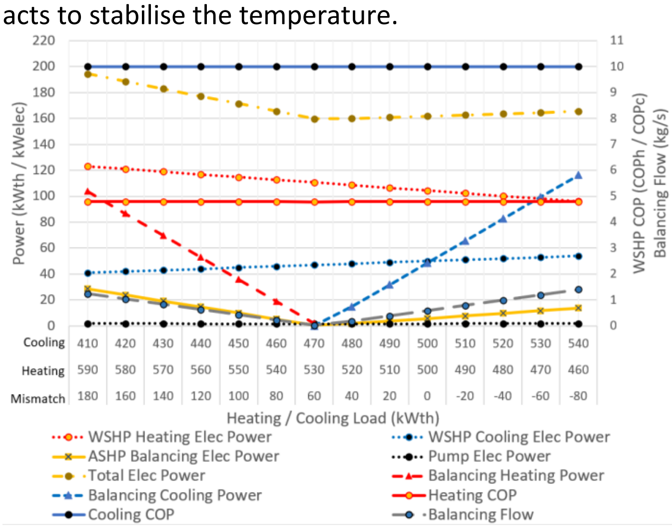

Fig. 6. Power/COP/Mass Flow – Active Control 5GDHCN

The optimal operating point in terms of electrical power consumption is again achieved when the network is heating-dominated by a magnitude of 60kW$_{th}$. If the operating point moves further towards the heating-dominated region, at substation 1 the COP of the WSHP falls slightly, and the mass flow increases. The balancing ASHP supplies more heating power. If the operating point moves further towards the cooling-dominated region, at substation 2 the COP of the WSHP falls slightly, and the mass flow increases. The balancing ASHP supplies more cooling power. In both cases this increases the electrical power demand of the balancing ASHP and circulation pump, and marginally increases the electrical power demand of the WSHP. It should be noted compared to Case One, the mass flow rate does not increase exponentially when moving away from the optimal operating point. This is because the WSHP COP remains relatively constant.

The optimal operating point is shifted towards the heating-dominated region because of the interaction of the WSHPs with the 5GDHC network:

- The COP of the heating WSHP is lower than the cooling WSHP, due to the larger ΔT between the hot pipeline and heating temperature at the consumer, compared to the ΔT between the cold pipeline and cooling temperature at the consumer.
- When the heating and cooling loads are perfectly balanced, the heat power extracted from the 5GDHC network by the heating WSHP is lower than the heat power injected by the cooling WSHP.
- By biasing the network towards a heating-dominated mode, the heat power extraction and injection by the WSHPs is balanced.
- In the case of the network with free floating temperature, this provides the optimal network supply temperatures to maximise COP.
- In the case of the network with active control of temperature, the balancing thermal power is minimised.
- In both cases, these conditions lead to minimisation of balancing mass flow and total electrical power.

The operating point which results in the lowest electrical power consumption will be shifted if any of the parameters listed are changed:

- Hot or chilled water temperature at the consumer
- Outlet temperature of substations
- Water temperature supplied by balancing units
- Ambient ground or air temperature

6. CONCLUSIONS

The design of a 5GDHC network must consider a variety of factors. For a network with free floating pipeline temperature, the balance of heating and cooling loads is critical. If the network becomes excessively dominated by either heating or cooling loads, the temperature of the hot and cold pipe will tend to converge, causing the COP of the WSHPs to fall, and consequently the mass flow rate, pumping losses, and electrical power consumption will increase exponentially. For a network with active control of pipeline temperature, the balance of heating loads is less critical. A network with active control can operate with a larger mismatch between heating and cooling loads, however, the electrical power demand of the balancing ASHP and circulation pump is increased when the mismatch is larger.

ACKNOWLEDGEMENT

The authors would like to thank the EPSRC Supergen energy networks hub (EP/S00078X/2) and the Integrated heating and cooling networks with heat-sharing-enabled smart prosumers (EP/T022795/1) for their financial and technical support.

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APPENDIX

Input Parameter	***Unit***	***Value***
Pipe Diameter (D)	m	0.15
Pipe 1 Length (L)	m	400
Pipe 2 Length (L)	m	400
Pipe 3 Length (L)	m	600
Pipe Heat Loss Coefficient (λ)	W/m.K	0.2
Pipe Roughness (ε)	mm	1.25
Heating Load (Φ)	kW	Variable
Cooling Load (Φ)	kW	Variable
Heating Substation Outlet Temperature (To_1)	°C	10
Cooling Substation Outlet Temperature (To_2)	°C	30
Hot Pipe Balance Temperature (ThotSupply)	°C	30
Cold Pipe Balance Temperature (TColdSupply)	°C	10
Ambient Temperature (Ground)	°C	8
Ambient Temperature (Air) (Summer)	°C	20
Ambient Temperature (Air) (Winter)	°C	5
Heating Temperature at Consumer	°C	50
Cooling Temperature at Consumer	°C	7
WSHP Total System Efficiency	%	30
Circulation Pump Efficiency	%	65
Pressure at Critical Consumer	Bar	1
Heat Exchanger Head Loss	Bar	0.5
Output Parameter	***Unit***	***Value***
ṁ1 (pipe mass flow)	kg/s	-
ṁ2 (pipe mass flow)	kg/s	-
ṁ3 (pipe mass flow)	kg/s	-
ṁq1 (node mass flow)	kg/s	-
ṁq2 (node mass flow)	kg/s	-
ṁq3 (node mass flow)	kg/s	-
Thot1 (Node Temperature)	°C	-
Thot2 (Node Temperature)	°C	-
Thot3 (Node Temperature)	°C	-
Tcold1 (Node Temperature)	°C	-
Tcold2 (Node Temperature)	°C	-
Tcold3 (Node Temperature)	°C	-
COP1 (Coefficient of Performance) (WSHP)	-	-
COP2 (Coefficient of Performance) (WSHP)	-	-
COP3 (Coefficient of Performance) (ASHP)	-	-
Network Heat Injection (ΦNetwCool)	kW	Variable
Network Heat Extraction (ΦNetwHeat)	kW	Variable

Table 1. Input and Output Parameters

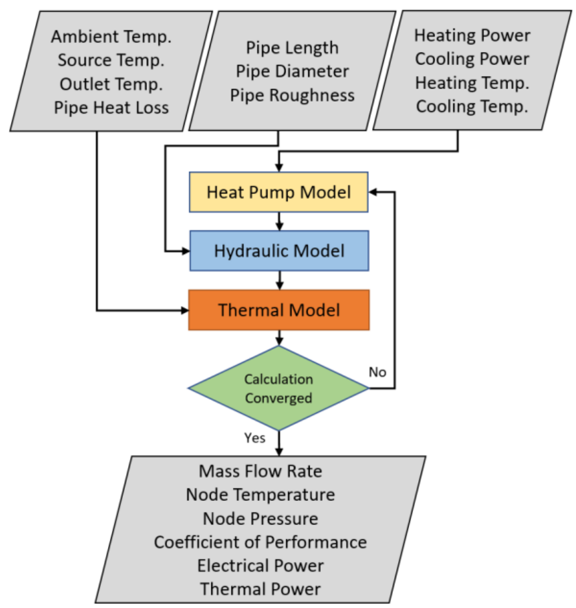

Fig. 7. Combined 5GDHC Model