



The 15th International Symposium on District Heating and Cooling

Essential improvements in future district heating systems

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Abstract

The major common denominator for future efficient fourth generation district heating systems is lower temperature levels in the distribution networks. Higher efficiencies are then obtained in both heat supply and heat distribution. Heat supply becomes more efficient with respect to combined heat and power, flue gas condensation, heat pumps, geothermal extraction, low temperature excess heat, and heat storage. Heat distribution becomes more efficient from lower distribution losses, less pipe expansion, lower scalding risks, and plastic pipes. The lower temperature levels will be possible since future buildings will have lower temperature demands when requiring lower heat demands. This paper aims at providing seven essential recommendations concerning design and construction strategies for future fourth generation systems. The method used is based on a critical examination of the barriers for lower temperature levels and the origins of high return temperatures in contemporary third generation systems. The two main research questions applied are: Which parts of contemporary system design are undesirable? Which possible improvements are desirable? Key results and the corresponding recommendations include temperature levels for heat distribution, recirculation, metering, supervision, thermal lengths for heat exchangers and heat sinks, hydronic balancing, and legionella. The main conclusion is that it should be possible to construct new fourth generation district heating networks according to these seven essential recommendations presented in this paper.

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Peer-review under responsibility of the Scientific Committee of The 15th International Symposium on District Heating and Cooling.

Keywords: Low-temperature; System design; Recirculation; Thermal lengths; Hydronic balancing

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1. Introduction

1.1. Policy

District heating systems are an important component in achieving future sustainable energy systems. The main idea is to utilise heat from sources otherwise unutilised [1, 2]. Effectively, this decrease energy demand and dependency of energy imports. Furthermore, implementation of district heating systems reduces the strain of scarce energy resources. Lower system costs and less anthropogenic climate change is a ripple effect of more district heating.

Due to the local nature of district heating systems, the technology has often been overlooked in international policy assessments. This did, however, change in the Heat Roadmap Europe studies [3], wherein it was concluded that the European Union may reach its target of annual greenhouse gas emissions reduction to a lower cost with district heating compared to other proposed alternatives. Furthermore, the economic value of district heating was shown to be higher in a future scenario with a large degree of end-use energy efficiency measures [3] compared to a scenario with no end-use energy efficiency measures [4], when related to the reference alternative.

Some major recognition of district heating at a policy level can be observed in the United Nations Environment Programme report ‘District Energy in Cities’ [5] and by the European Union heating and cooling strategy [6, 7].

1.2. Technology change

In order to meet future conditions, the current district heating technology must be further developed. This technology has been referred to as third generation of district heating systems (3GDH) [2]. Hereby, the term for future development have been labelled as the fourth generation of district heating systems (4GDH), which has been defined in [2]. The basic idea is to maintain the best part of the current 3GDH technology while weak parts should be enhanced in 4GDH design.

1.3. Future conditions

Heat demands are expected to be lower in future buildings, as new buildings within the European Union are required to have a very high energy performance, referred to as nearly zero-energy buildings, from 2019 for public authorities and 2021 for others [8]. Furthermore, buildings which undergo major renovation should be upgraded to meet minimum energy performance requirements [8].

Lower heat demands entail opportunity, as adequate temperature requirement for space heating decrease as well, enabling lower temperature levels in distribution. In a long term structural perspective, levelling of adequate temperature requirements between supply, distribution, and end-use increase performance as there will be a better quality match between supply and demand and thus a better exergy utilisation rate [9].

Increased heat distribution costs are a consequence of future low heat demand energy systems. This relation is of concern regarding feasibility of future district heating systems. However, the distribution cost component generally constitutes a smaller proportion of the total cost structure and thus have a moderate impact on feasibility [10].

Improved efficiencies in district heating systems are also centred on lower temperature levels in the distribution networks. In heat supply, low-temperature operation entail improved performance in combined heat and power, flue gas condensation, heat pumps, low temperature excess heat, geothermal extraction, solar thermal, and heat storage [11]. In heat distribution, low-temperature operation entails improvements by lower distribution losses, less demand for pipe expansion, lower risk for scalding, and potentially use of other piping materials, e.g. plastics [11].

Currently identified barriers to lower temperature levels in district heating systems consist of demand side limitations, legionella issue, substations faults, and by-pass flows in networks [11]. From a technical system design perspective it is a challenge to overcome barriers which will allow low-temperature district heating operation. In current documentation of low-temperature systems, no annual average system return temperature below 30 °C has been recorded [11].

1.4. Implementation

Several possible options and alternative scenarios for transitions toward district heating systems with lower temperature levels in distribution networks are conceivable. The market is segmented into many different customer types with varying requirements of heat demands, for instance residential, commercial, and industrial. Four example areas of district heating expansion are described below, all of which may be classified in the spectrum of low or high heat density areas, i.e. single- or multifamily house areas, respectively:

- Development areas where prior district heating exist in surrounding urban area
- Development areas where no prior district heating system exist in surrounding urban area
- Urban areas where prior district heating system exist
- Urban areas where no prior district heating system exist

To maintain low-temperature level in new development areas wherein heat network operation already is established, concurrent operation are a feasible solution. Concurrent operation may be designed as:

- Parallel networks with different temperature levels
- Division into primary and secondary networks through hydraulic separation by central substations
- Supply-to-supply connections, cascading from customers with high temperature requirements to customers with lower temperature requirements
- Return-to-return connections, cascading from customers with medium temperature requirements to customers with lower temperature requirements

1.5. Aim

The aim of this paper is to provide a conceptual overview for desirable system design improvements in 4GDH for new distribution networks supplying heat to new buildings. The overarching goal is to elaborate the idea and initiate a discussion about proposed essential improvements regarding the issue of barriers, which obstruct transition to low-temperature operation. Thereby introducing, a potential path towards district heating systems with undisturbed annual average return temperatures lower than 30 °C.

This paper emphasise implementation of improved district heating design in residential development areas of high building density areas, i.e. multifamily house areas. The paper presumes a European harmonization perspective, availability of district heating supply, construction of buildings with very high energy performance, and expansion of district heating coordinated with simultaneous construction.

This paper is based on a qualitative approach. A critical examination perspective is applied, by searching for answers to the two main research questions:

- Which parts of contemporary 3GDH design is undesirable?
- Which potential improvements are desirable in future 4GDH design?

2. Temperature levels

2.1. Undesirable 3GDH design

The temperature levels differ vastly between different networks, as may be observed [12]. Collected data on annual average supply and return temperatures display for Sweden 86-47 °C and for Denmark 78-43 °C, respectively. Similar national averages are not available for other countries, but corresponding system examples varies between 77 and 110 °C for supply temperatures and 41 and 76 °C for return temperatures.

The potential annual supply and return temperature levels achievable in contemporary system design are estimated to be 69 and 34 °C, respectively, according to simulations performed by [13].

Differences between actual and simulated network temperatures depend mainly on by-pass flows and temperature errors in substations and customer heating systems.

In a study which analysed many district heating substations, it was concluded that 74 % of the substations exhibited an erroneous function [14]. A brief overview of different temperature errors identified can be found in [1], these errors are based on 520 temperature errors found in 246 substations during 1992-2002.

The current higher temperature levels disable the use of low cost low temperature heat supply as these heat sources is only feasible at current supply temperature levels with the use of heat pumps.

2.2. Desirable 4GDH design

The lower boundaries for supply temperature in district heating systems are typically confined by the requirement to avoid legionella in domestic hot water preparation. As space heating demands typically may be fulfilled even at lower temperatures, particularly in buildings with very high energy performance.

There are of course other technical solutions which allows for lower temperature levels, such solutions does however require some form of auxiliary heating at the customer end of the system, commonly referred to as cold district heating systems. Whereas, the lower boundaries for return temperature in district heating systems typically are confined by the ambient indoor temperature. The envisioned temperature levels of future district heating systems are 50 and 20 °C for supply and return, respectively.

3. Recirculation

3.1. Undesirable 3GDH design

Primary supply water is recirculated into the return pipe is a common contemporary system design to counteract supply temperature degradation.

Traditionally a summer problem, by-passes are built into the system to maintain sufficient primary temperature when network flow is low due to relative high heat losses at low space heating demands. The winter problem of freezing of non-used pipes is also managed with by-passes. These by-pass flows may be intentional, as described previously, but may also be unintentional, i.e. remnants or mistakes from older network expansion.

This traditional recirculation increases temperature levels in thermal networks, decrease efficiency, and increase costs [15].

By estimates, 10-20 % of total annual flows in district heating systems are by-passes. With regard to achieving an undisturbed return temperature, by-pass flow in thermal networks is a major concern in heat distribution.

3.2. Desirable 4GDH design

Regardless of situation, by-passes are an undesirable component in future system design. Thus, future design should contain no by-passes between primary supply and return pipe. This should be achievable with the implementation of three-pipe systems. In which the smaller third pipe is used to recirculate supply temperature water when required, thus avoiding temperature degradation of supply flow and temperature contamination of return flow due to by-passes in the system.

4. Metering

4.1. Undesirable 3GDH design

At present, the dominating norm of district heat supply is collective metering in multi-apartment buildings, resulting in a low resolution of individual customer information.

The European energy efficiency directive [16] states that use of individual meters measuring use of heating in multi-apartment buildings supplied by district heating is beneficial only in buildings where radiators are equipped with thermostatic radiator valves thus enabling customers to have a means to control their own usage. This is not

strictly true as there are additional benefits of individual metering, e.g. apartment metering enables the potential to isolate individual faulty substations which lead to increased return temperatures [14].

Furthermore, the energy efficiency directive [16] states that from 2017 multi-apartment building supplied by district heating shall install individual meters to measure use of heating, cooling, and domestic hot water for each apartment where technically feasible and cost-efficient. Hence, the current collective metering does not fulfil future legal requirements for individual metering.

4.2. Desirable 4GDH design

A transition to individual apartment substations will give a direct solution for providing individual metering according to the energy efficiency directive. The implications of a change from collective to individual metering will be:

- Heat transfer between apartments may occur if indoor temperature settings vary between apartments effectively allowing apartments with low temperature settings to be heated by other residents heating
- Residents may, if accessible, alter the ventilation systems in the interest of saving on heating expenses. For instance, by reducing or eliminating ventilation air flow, less heat is required. In doing so residents endanger their own health and risk damages on the building itself [17]
- Heat losses associated with hot water circulation is allocated to the heat supplier with individual apartment substations

These implications must be considered when implementing individual apartment substations.

5. Supervision

5.1. Undesirable 3GDH design

A deficit of individual customer information hinders heat suppliers to counteract temperature errors as there is no access to information to act upon.

Temperature errors can currently exist for months or years before discovered and eliminated, this situation is undesirable

5.2. Desirable 4GDH design

Use of continuous commissioning by increased implementation of information and communications technology (ICT) would alleviate the work to counteract temperature errors in substations and customer heating systems. Since, with increased capacities to retrieve, transmit, and analyse information electronically in a digital form a situation with affluence of individual substation information emerge.

6. Thermal lengths, heat exchangers

6.1. Undesirable 3GDH design

Current use of heat exchangers in substations creates an average difference in temperature levels of about 10-15 °C between the district heating network and the customer heating systems.

Sizing of heat exchangers have in Sweden typically been dependent on design requirements in industry standards. These industry standards use the performances indicator of thermal length, expressed as number of thermal units (NTU) for heat exchangers. These thermal lengths have increased from about two during mid-1960s to four today, regarding space heating. Development of heat exchangers for domestic hot water has seen similar improvements of required thermal lengths. Such design of thermal length in substation heat exchangers will be insufficient under future design conditions.

6.2. Desirable 4GDH design

An increase of thermal length is required to meet future design requirements of decreased temperature levels. By increasing thermal length in substation heat exchangers the mean logarithmic temperature gap between primary and secondary side is shortened. By introduction of heat exchangers with a thermal length of 6-8, which is 1.5-2 times longer than contemporary design, the mean logarithmic temperature will be reduced to around 5-10 °C.

7. Thermal lengths, radiators

7.1. Undesirable 3GDH design

By tradition high radiator temperatures have been used in order to reduce radiator sizes at high heat demands.

The secondary space heating system may also be assessed with the thermal length concept, since a radiator is a heat exchanger. Contemporary design temperature levels for radiator systems are in older buildings 80-60 °C and in newer buildings 60-40 °C, with a constant room temperature of 20 °C this yield thermal lengths of 0.4 and 0.7, respectively.

7.2. Desirable 4GDH design

To maintain a high temperature difference it is important to consideration radiator sizing. In future buildings with low heat demands, requirement of radiators sizing may be reduced. It is however desirable to have larger or at least to retain contemporary radiator sizing in order to facilitate the issue of high temperature difference in space heating system.

Envisioned temperature levels of future systems require change of design temperatures in radiator systems. Projected design parameters entail longer thermal lengths; a feasible setting for radiator supply and return temperatures are 45-25 °C, with a constant room temperature of 20 °C. The defined conditions for new developments result in a thermal length of 1.5, an increase by a factor two compared to contemporary system design.

Floor heating is an alternative to radiators for space heating, with an average supply temperature just a few degrees above room temperature [2]. A case study performed in [11], suggest a supply temperature for floor heating of about 30 °C, with approximately a 3 °C temperature drop to maintain an even temperature on the heated area. The advantage with floor heating is lower requirements of supply temperature levels, while the disadvantage is slightly higher return temperatures, compared to radiators.

8. Hydronic balancing

8.1. Undesirable 3GDH design

Unbalanced radiator systems inadvertently cause overflows in some parts of the system; these can be apprehended as by-passes creating higher return temperatures.

It is difficult to obtain a sustainable and reliable hydronic balancing in radiator systems as the conventional way of managing hydronic flow regulation is through manual setting of balancing valves and radiator valves [18]. Manual hydronic balancing management is labour intensive as the whole system initially requires balancing. Readjustment may be necessary as misallocations may occur and even in a balanced system additional balancing may be required as time progress due to changes, intended or unintended, in existing hydraulic system.

8.2. Desirable 4GDH design

In order to avoid excessive amounts of endeavours to maintain a functional space heating system, perfect allocations are desirable. The issue of hydronic balancing become less extensive with the introduction of individual apartment substations. To maintain a high temperature difference between supply and return flow, automated hydronic balancing is although desirable.

Introduction of flow valve limiters at radiator outlets in customer space heating systems would ensure a certain return temperature, if flow is regulated with regard to outlet temperature. By limiting flow, heat emission to ambient heated space is ensured. Flow valve limiters can regulate radiators individually without impact of flow allocation of the overall system.

9. Legionella

9.1. Undesirable 3GDH design

Growth of the Legionella bacterium is a concern in domestic hot water preparation. The bacteria exhibit stagnation in growth at 46 °C and the concentration of bacteria decrease rapidly with higher temperatures, according to current knowledge [19].

Recent research suggest that the bacteria may grow in higher temperatures as well [20]. If such results become more apparent then it becomes even more significant to have efficient domestic hot water preparation.

The Legionella issue is related to slow domestic hot water preparation with long residence time in hot water circulation and storages.

9.2. Desirable 4GDH design

The key to this issue is low water volumes at secondary side and fast domestic hot water preparation, i.e. instantaneous discharge by heat exchanger, in order to obtain short residence times. District heating substations are able to provide this.

By implementation of individual apartment substations, large networks of hot water circulation, with volumes exceeding three litres, may be avoided in large buildings. Meanwhile, the requirement of domestic hot water circulation is avoided with individual apartment substations which further alleviate the issue of Legionella.

The German regulation for domestic hot water is commonly referred to in relation to low temperature district heating operation [21]. This regulation states that domestic hot water may occur without any specific safety measures against Legionella as long as total volume in the piping does not exceed three litres. In addition the regulation states that for small systems, i.e. on an individual household level, a recommended temperature of 60 °C is suggested, while it also states that temperatures below 50 °C should be avoided at all times.

Table 1. Summary of the overall and seven identified undesirable contemporary system design areas with corresponding desirable system design improvements

Location	Design area	3GDH Traditions	4GDH Requirements	4GDH Actions
System	Temperature levels	Sweden 86-47 °C Denmark 78-43 °C	Vision of 50-20 °C	No temperature errors, longer thermal lengths, and more efficient customer heating systems
Network	1. Recirculation	By-passes	No by-passes	Three-pipe system
Substation	2. Metering	Collective	Individual	Apartment substations
Substation	3. Supervision	Many temperature errors	Continuous commissioning	ICT Supervision
Substation	4. Thermal lengths, heat exchangers	About 4	About 6-8	Longer thermal lengths
Customer	5. Thermal lengths, radiators	About 0.4-0.7	About 1.5	Longer thermal lengths
Customer	6. Hydronic balancing	Many misallocations	Perfect allocations	Automated hydronic balancing
Customer	7. Legionella	Hot water circulation and sometimes hot water storages	No hot water circulation and no hot water storages	Apartment substations

10. Discussion

The main actions for enhancing the 4GDH system design are three-pipe systems for heat distribution and individual apartment substations for customer interfaces. Enhanced individual apartment substations, have several important synergy advantages as they:

- fulfil future legal requirements from the European energy efficiency directive concerning individual metering
- increase resolution of which temperature errors may be identified by metering
- eliminate the demand for hot water circulation in buildings
- decrease volume of water in the secondary side, which implies less risk of legionella
- reduce the demand for complex manual hydronic balancing, as secondary system for space heating become limited to apartment level rather than building level
- will allow for large harmonized manufacturing volumes of universal components, such as heat exchangers, furthering the perspective of economy-of-scale

By ensuring coordination in early stages of project planning, agreements of new and improved technological solutions can be achieved. Also, coordination of pipeline construction with other building construction infer typically halve the construction cost compared do pipeline construction in pre-existing buildings areas [1].

11. Conclusion

In this paper, seven specific areas which imply barriers to achieve lower temperature levels are identified. Furthermore, commensurate technical system improvements to counteract the seven specific areas of barriers to achieve lower temperature levels in future district heating are suggested.

With respect to the first research question, the following undesirable design areas in contemporary 3GDH systems have been identified:

- By-passes contaminate return flow and prevent an undisturbed return temperature in thermal networks.
- Collective metering does not fulfil future legal requirements for individual metering.
- Lack of systemic supervision of substations by district heating utilities, result in omission to rectify a large number of temperature errors.
- Current thermal lengths in substation heat exchangers are too short hinder transition towards low temperature operation.
- Short thermal lengths in customer radiator systems are remnants from a period of high heat demands.
- Many misallocations occur in customer radiator systems due too high complexity of manual settings for hydronic balancing and radiator valves.
- High residence time and large volumes of domestic hot water induce greater risk of legionella growth in customer systems.

With respect to the second research question, the following desirable actions in future 4GDH systems have been identified:

- Three-pipe systems in order to supply water circulation without any temperature contamination of the true return temperature.
- Apartment substations in order to provide individual metering and supervision together with avoidance of Legionella growth and major hydronic balancing problems.
- Longer thermal lengths in heat exchangers and radiator systems in order to reduce temperature differences at heat transfer.

By conducting this work we have identified seven important design areas to be considered for implementation of 4GDH systems. Only one design areas concern the distribution network, while three design areas are associated to the customer interface and three design areas are related to the customer heating systems.

Hereby, concluding that the essential key actions for transition towards 4GDH in new distribution networks for new buildings are located in substations and customer heating systems close to the final heat use.

Acknowledgements

The present work was performed within the research project Future District Heating Technology financed by Fjärrsyn – the Swedish district heating research programme funded in collaboration by the Swedish Energy Agency and the Swedish District heating Association.

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