Development of a new generation of cold district heating systems with water as heat transfer medium

Peer Huber[1], Harald Drück[1], Bernd Hafner[2] and Ralf Dott[2]

[1] Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE)
University of Stuttgart, Germany

[2] Viessmann Climate Solutions SE, Allendorf (Eder), Germany

Abstract

The purpose of cold district heating systems is to cover the heating and cooling demand of consumers connected to the district heating network. Generally, they consist of a thermal energy source, a thermal energy store, heat pumps and a cold district heating network for distribution. Some of these cold district heating systems use thermal energy sources like an ice store or solar thermal air-brine-collectors supplying temperatures below the freezing point of water and therefore in these conventional cold district heating systems a mixture of water and antifreeze as heat transfer medium is necessary. As the use of antifreeze leads to ecological and economic disadvantages, the development of a new generation of cold district heating systems with water as heat transfer medium is being performed. In this paper this new innovative system concept and a simulation model of this system concept is presented. Furthermore, an evaluation of the operation strategy of the ice store integrated into the overall system based on simulation results is presented. In addition, the results of a simulation study related to an energetic comparison of heat losses and gains between the new innovative cold district heating network using water and a conventional network using a mixture of water and antifreeze are introduced. In conclusion, the evaluations performed clearly show the important role of the ice store as a seasonal thermal energy store and the higher heat losses of the new innovative cold district heating network compared to the conventional network. It is expected that the new generation of cold district heating systems with water as heat transfer medium has ecological and economic advantages compared to conventional cold district heating systems. Demonstrating this is part of the ongoing research project "SolKaN2.0" related to the development of a new generation of cold district heating systems.

Keywords: Cold district heating system, cold district heating network, 5GDHC, heat transfer medium, antifreeze, ice store, solar thermal air-brine-collector, TRNSYS simulation

1. Introduction

Cold district heating systems are also known as the fifth generation of district heating and cooling (5GDHC) systems. During the evolution of district heating and cooling networks the temperatures in the network distributing the heat decreased continuously from generation to generation. As described by Lund et al. (2014) the first generation started with steam as heat transfer medium and temperatures up to 200 °C followed by pressurized hot water with temperatures mostly above 100 °C in the second generation. In the third generation the temperatures decreased often below 100 °C, whilst in the fourth generation they are between 30 and 70 °C. With the most recent fifth generation of cold district heating systems this evolution continues towards lower temperatures between −15 and 30 °C.

The main reason to use such systems with low temperatures is the reduction of heat losses to the environment. The use of relatively low temperatures is also supported by the continuously improving energetic building standard that makes it possible to use heating systems with relatively low flow temperatures. Furthermore, the usage of distribution temperatures below approx. 15 °C also offers the possibility to use the district heating network for both, heating and cooling. However, the supply of domestic hot water is challenging with relatively low temperatures.

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2. State of the art of cold district heating systems

Generally, cold district heating systems consist of thermal energy sources such as solar thermal air-brine-collectors and a thermal energy store, e.g. an ice store, heat pumps and the cold district heating network for the distribution of the thermal energy. In Figure 1 the thermal energy sources are located on the left hand side, the heat demand of the decentral consumers can be seen on the right hand side and in between the cold district heating system and the substations with decentral heat pumps are positioned.

Some of these systems use thermal energy sources supplying temperatures below the freezing point of water. To perform a heat transfer between the thermal energy sources and the cold district heating network in conventional cold district heating systems the usage of a mixture of water and antifreeze as heat transfer medium is required. However as elaborated in the following chapter, the use of antifreeze results in ecological and economic disadvantages.

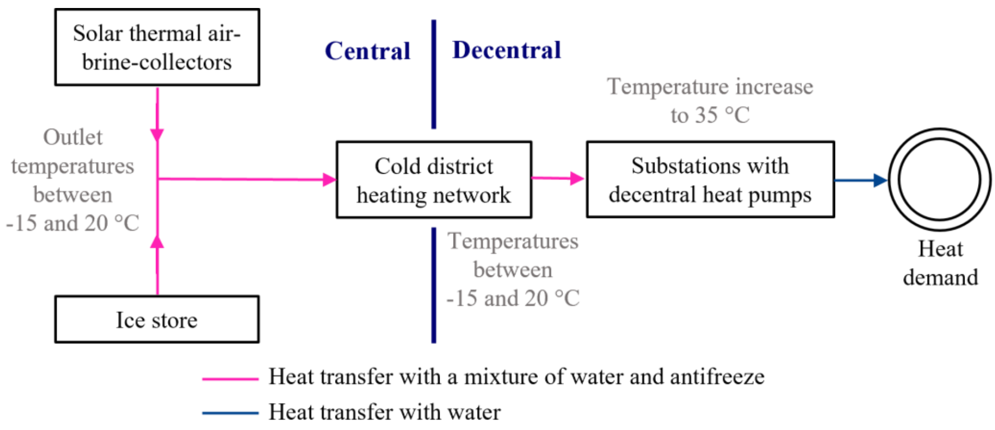

Fig. 1: Schematic set-up of a state of the art cold district heating system with solar thermal air-brine-collectors and an ice store as thermal energy sources and a mixture of water and antifreeze as heat transfer medium

3. Disadvantages using antifreeze in cold district heating systems

Major challenges of using antifreeze are several necessary security measures due to the classification of common antifreeze types as slightly water polluting. Therefore, depending on the individual requirements of the country, double-walled pipes and an automatic system for leakage detection must be implemented in the cold district heating network e. g. in Germany. Furthermore, the decentral substations which transfer the heat between the decentral heat pumps and the central cold district heating network must be equipped with collecting basins for the antifreeze medium in case of a leakage. These measures lead to increasing costs from an economic point of view on the one hand. On the other hand, the collecting basins require additional valuable space in the buildings and are therefore related to additional costs.

In addition, the viscosity of the mixture of water and antifreeze is higher, and the specific heat capacity is lower compared to pure water. This leads to an increased electric energy demand for the pumps installed in the different cycles operated with the mixture of water and antifreeze as heat transfer medium.

Moreover, the mixture of water and antifreeze is significantly more costly than water. From an ecological point of view, the production of the mixture is associated with additional greenhouse gas emissions.

To conclude, the replacement of the mixture of water and antifreeze with water is a reasonable improvement of cold district heating systems. Therefore, this is the key aspect of the development of a new generation of cold district heating systems, which is described in the following chapter.

4. New generation of cold district heating systems with water as heat transfer medium

In Figure 2 the schematic set-up of the new generation of a cold district heating system with water as heat transfer medium is shown. On the right side the heat demand of the decentral consumers is located. On the left side the solar thermal air-brine-collectors as thermal energy source and an ice store as thermal energy store are centrally positioned. Between the heat demand and the heat supply the cold district heating network distributes the heat using water as heat transfer medium.

Before the heat supplied by the thermal energy sources can be transferred into the cold district heating network a central heat pump is required to increase the temperature. This is necessary as the outlet temperatures of the solar thermal air-brine-collectors and the ice store can vary approximately between −15 to 20 °C. This also requires the use of a mixture of water and antifreeze for the heat transfer between the thermal energy sources and the central heat pump. But after the temperature increase by the central heat pump water can be used as heat transfer medium in the main part of the district heating network.

Additionally, decentral heat pumps are located in the respective buildings to cover the heat demand using the cold district heating network as their heat source. In this case the temperature is increased from around 5 to 15 °C to 35 °C which is suitable for floor heating systems.

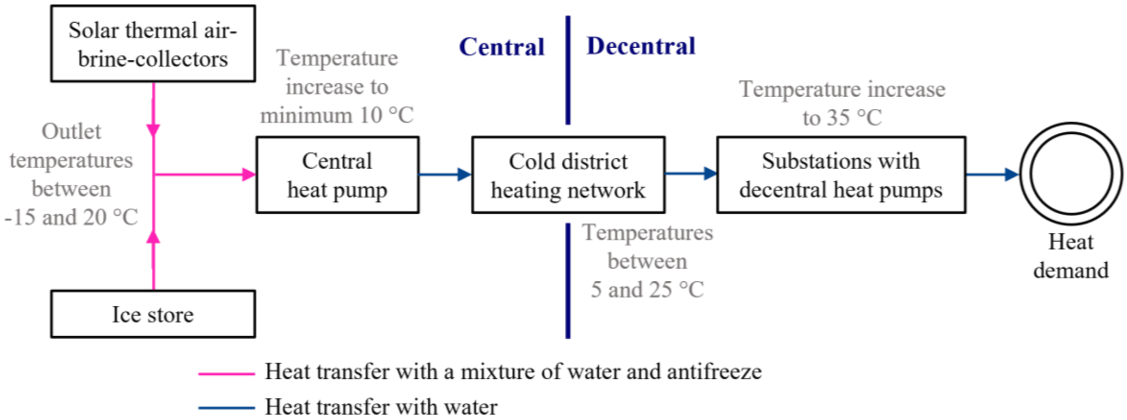

Fig. 2: Schematic set-up of the new generation of a cold district heating system supplying heat to the customers with water as heat transfer medium

Figure 2 and the previous explanation describe the heat supply by the cold district heating system in case of a space heating demand. Additionally, the system is suitable for the extraction of heat from the buildings for cooling purposes in summer. The extracted heat can then be stored in the ice store or dissipated by the solar thermal air-brine-collectors to the environment.

Unfortunately, e.g. for German weather conditions in times with cooling demand the temperatures of the ambient air are mostly too high to use the environment directly by the solar thermal air-brine-collectors as heat sink. Additionally, from an economic point of view the ice store capacity cannot be designed to store the cooling demand of the whole cooling season and will reach its maximum capacity at about 20 °C water temperature in the ice store within the first weeks of summer based on the experience from pilot plants which were part of the preceding research project ‘Development of integrated solar supply concepts for climate-neutral buildings for the “city of the future” (Sol4City)’. Therefore, in an additional operating mode the central heat pump can be used to actively extract heat from the buildings by using them as heat source, as shown in Figure 3. The resulting heat at a high-temperature level of about 40 °C is transferred to the environment by the solar thermal air-brine-collectors.

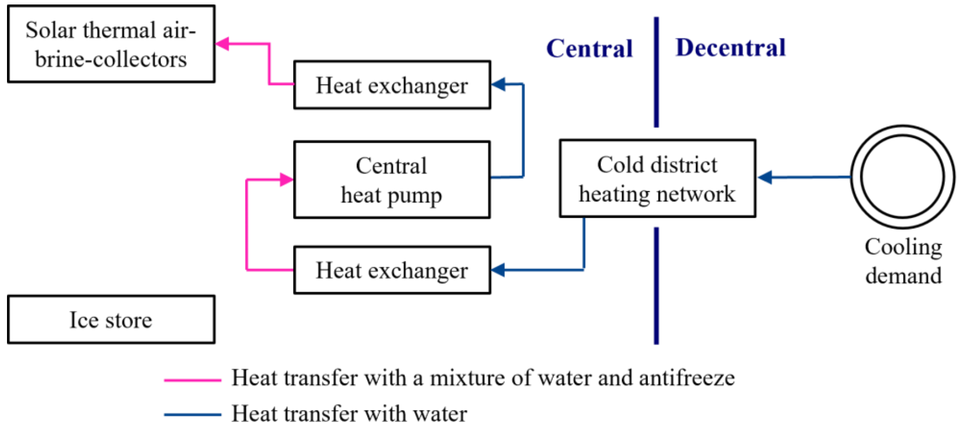

Fig. 3: Schematic figure of the new generation of a cold district heating system using the central heat pump to actively cool the decentral buildings and transfer the heat to the environment by the solar thermal air-brine-collectors

In addition, the central heat pump may actively cool the ice store at night and hence decrease the temperature of the water inside the store. The gained capacity for heat can then again be used as a heat sink for the cooling of the buildings by day. Compared to cooling the buildings via the central heat pump during the day directly, it is more efficient to operate the central heat pump during the night when the ambient temperatures are lower. Theoretically there is also the possibility to passively cool the ice store in nights with significantly lower ambient temperatures compared to the water temperature in the ice store. As those cold nights are rare in summer for German weather conditions, this passive precooling of the ice store is not often in use.

As described previously the ice store can be regenerated or heated respectively on the one hand with the extracted heat from the buildings for cooling purposes. On the other hand, heat gains from the solar thermal air-brine-collectors can be used to melt the ice and / or increase the temperature of the water inside the ice store.

In conclusion the main innovative aspect of this system is the use of water as heat transfer medium in the district heating network. However, this results in the need for an additional central heat pump. To assess this new innovative system, in chapter 6 and 8 various investigations are performed by means of numerical simulations with the software TRNSYS. This simulation model developed for this purpose is described in more detail in the following chapter 5.

5. Simulation model

The simulation model of the new innovative cold district heating system has been created with the simulation software TRNSYS. This software is commonly used for dynamic simulations of energy supply systems. To model the overall cold district heating system sub-models for every component are used. The most important sub-models are presented in the following.

For modeling the solar thermal air-brine-collectors the TRNSYS "Type 832" is used. The characteristic values for the collector type "SLK-600" which are used in this simulation to parameterize the collector model were determined by Fischer et al. (2021). Like other components of the system simulation this model receives weather data for a location near Stuttgart, Germany.

Both the central and the decentral heat pumps are modeled by the TRNSYS "Type 212" which was developed at the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE). This model determines the heat output and the electrical energy demand based on characteristic curves depending on the inlet temperature in the evaporator and a linear interpolation approach. Those characteristic curves are quadratic polynomials which are created based on performance data provided by the heat pump manufacturer.

Small hot water stores are used in this system to allow a consistent operation of the heat pumps and therefore increase their efficiency and also to hydraulically separate different parts of the cold district heating system from each other. To model those hot water stores the TRNSYS "Type 340" by Drück (2007) is implemented in the simulation model. These stores are directly charged and discharged without using a heat exchanger. In addition to thermal stratification inside the store the model also considers heat losses to the environment.

The cold district heating network is simulated with the TRNSYS "Type 710" and will be described further in chapter 7.

To simulate the ice store the TRNSYS "Type 343" developed by Hornberger (1994) is used. This model includes an underground storage tank with water as storage medium and pipe coils inside the store as heat exchanger. Inside these pipe coils a mixture of water and antifreeze must be used in order to generate ice inside the store. In addition, the model considers heat gains from the surrounding earth and offers the possibility to configure the store dimensions and material properties of the storage material, pipe coils, storage medium, heat transfer medium and the surrounding earth. In the following chapter 6 simulation results focusing on the ice store are presented.

6. Heat balance and state of charge of the ice store

The ice store has the ability of balancing seasonally varying heating and cooling demands over a long period of time. Additionally, heat gains by solar radiation can be stored in the ice store and used for heating demands if required. In the following the operation of the ice store is presented with a monthly heat balance and the state of charge for the time of one year based on results of the previously presented simulation model.

In Figure 4 heat inputs are represented with positive bars and heat outputs with negative bars. Heat inputs occur through regeneration with solar heat gains or with heat extracted from the buildings for cooling purposes and through heat gains from the earth surrounding the ice store. Heat outputs occur in times with heating demands from the buildings and therefore in this case the ice store is used as a heat source for the central heat pump. In addition, heat can be actively or passively extracted from the ice store to precool it during summer nights as described in chapter 4.

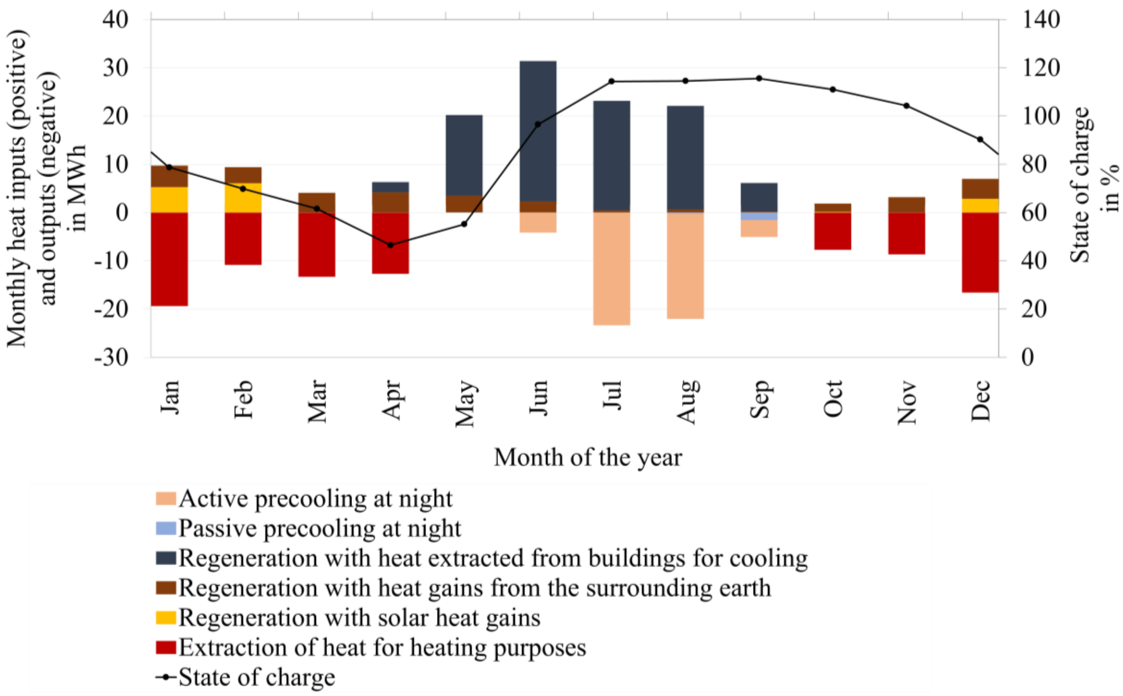

Fig. 4: Monthly heat balance and monthly average state of charge of the ice store over the period of one year

The development of the state of charge of the ice store is also shown in Figure 4. This state of charge is defined as 100 % for a state with only liquid water and a water temperature of 0 °C. With an increasing share of solid water or respectively ice, the state of charge is continuously decreasing below 100 %. Theoretically, at a state of charge of 0 % all liquid water would be solid ice. But the ice store is operated only until around a state of charge of 20 %, as with an increasing ice layer around the pipes of the heat exchanger the efficiency of the heat transfer is decreasing. Additionally, a completely frozen ice store would result in tensions in the material of the storage wall as ice has a higher volume than liquid water. With a rising water temperature above 0 °C the state of charge can increase above 100 % until the water reaches the maximum temperature of 20 °C. This maximum temperature is due to avoid material fatigue in the storage walls.

With the beginning of the heating season in October the state of charge is decreasing as more heat is extracted from the ice store compared to heat gains from the surrounding earth and the solar thermal air-brine-collectors. This continues throughout the whole heating season until April. Although regeneration through solar heat gains reduces the discharging of the ice store in some months the system control intentionally limits this regeneration to provide enough capacity for cooling purposes at the end of the heating season. With the beginning of the cooling season this capacity is used to store heat extracted from the buildings and thus the state of charge is increasing from May to July until it reaches its previously mentioned maximum. Then the active and on a small scale the passive precooling of the ice store at night ensures to provide storage capacity for cooling during the day. Since the extraction of heat at night and the insertion by day compensate each other, the state of charge remains constant from July to September.

The results of the system simulation presented in this chapter clearly shows the essential role of the ice store as a seasonal thermal energy store integrated into a cold district heating system with heating and cooling demands.

7. Validation of the cold district heating network model

For the simulation of the cold district heating network the TRNSYS model “Type 710” originally developed by the Institute for Solar Energy Research in Hameln (ISFH) for horizontal ground heat collectors is used. It can be configured to model only one horizontal pipe buried in a specified depth below the surface.

As described by Hirsch (2016) the model can consider the heat exchange between the earth directly surrounding the pipe and the undisturbed earth. Therefore, undisturbed earth temperatures are calculated based on the Kusuda correlation by Kusuda and Archenbach (1965) and depending on the time of the year, the depth below the surface, the ambient temperature and various properties of the earth. This undisturbed earth temperature is not influenced by the heat exchange with the fluid. In contrast the area of the disturbed earth around the pipe is influenced by the heat exchange with the fluid, the heat exchange between the earth’s surface and the ambient air by convection and the influence of solar and thermal radiation on the earth’s surface. Finally, the heat related to the phase change between liquid water and solid water or respectively ice included in the earth is considered.

To validate the simulation results of the TRNSYS model “Type 710” the simulation results of the heat gains and losses at the flow pipe in the new innovative cold district heating network are compared with the results of a simplified analytical calculation of the heat exchange between the fluid and the surrounding earth. Within every timestep of the simulation the heat exchange is calculated by the following equation 1.

$$Q_i = U_{d,\mathrm{outer}} \cdot L \cdot P_{\mathrm{outer}} \cdot \left(\vartheta_{\mathrm{Earth},i} - \vartheta_{\mathrm{Fluid},i}\right) \cdot t_i \qquad \text{(eq. 1)}$$

Q_i	Heat exchange between fluid and earth within the timestep i in J
$U_{d,\mathrm{outer}}$	Heat transfer coefficient in relation to the outer diameter of the pipe in W m^{-2} K^{-1}
L	Pipe length in m
P_{outer}	Outer perimeter of the pipe in m
$\vartheta_{\mathrm{Earth},i}$	Temperature of the surrounding earth in timestep i in °C

$\vartheta_{\text{Fluid},i}$ Temperature of the fluid in timestep i in °C

t_i Time duration of timestep i in s

The calculation of the heat transfer coefficient considers the convective heat transfer between fluid and pipe and the conductive heat transfer within the pipe. The convective heat transfer has been calculated with the Nusselt correlation for a fully developed turbulent flow by Gnielinski (1975) and a mass flow of 42,908 kg h^{-1}. The heat transfer between the pipe and the earth is assumed to be ideal. This results in a heat transfer coefficient of 0.259 W m^{-2} K^{-1} in relation to the outer diameter of the pipe.

Regarding the pipe a length of 420 m, an inner diameter of 141.8 mm and an outer diameter of 298.2 mm are assumed. There are inner pipe walls and outer pipe walls, both made of polyethylene with a thermal conductivity of 0.38 W m^{-1} K^{-1} and a thickness of 9.1 mm. In between the inner and the outer pipe walls an insulation with a thickness of 60 mm and a thermal conductivity of 0.022 W m^{-1} K^{-1} is assumed.

The time duration of one timestep amounts to 12 minutes.

Like in the TRNSYS model "Type 710" the temperature of the surrounding earth is calculated with the Kusuda correlation by Kusuda and Archenbach (1965), which was already described at the beginning of this chapter.

As fluid temperature the mean value of inlet and outlet temperature of the flow pipe is used and assumed to be constant over the whole pipe length.

In Figure 5 the resulting monthly heat gains and losses calculated analytically are shown as black line. The analytical calculation does not consider the effects due to solar and thermal radiation and the heat exchange with the ambient air. In order to compare the results, those effects were also ignored by the simulation model in the first step. The resulting continuous grey line is shown in Figure 5. In comparison the simulation results are close to the results of the analytical calculation. Although, in the first month and the last five months of the year a higher difference between the simulation results and the analytical calculation compared to the other months can be observed. In further investigations it was recognized that those differences mainly occur in the time periods without mass flow through the pipe. It is assumed that especially in those time periods the fluid temperature used for the analytical calculation differs from the fluid temperature used in the model.

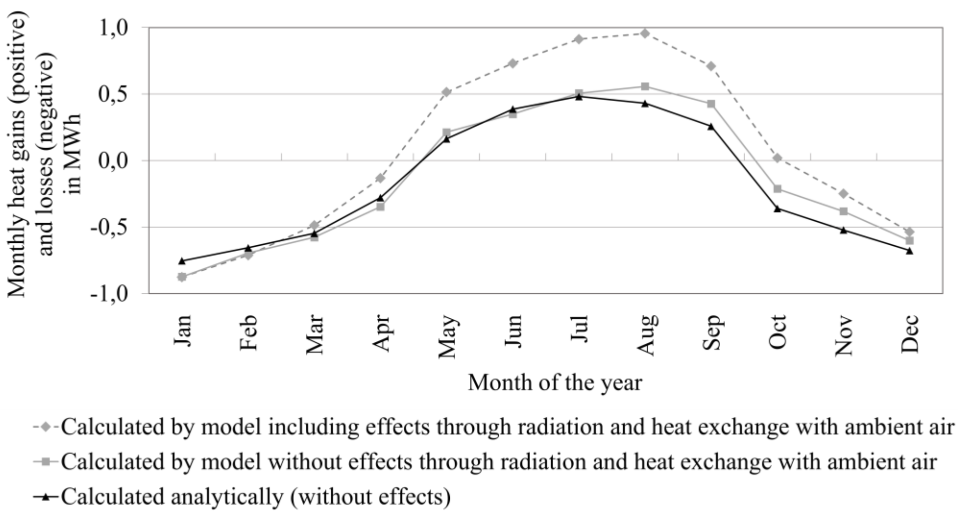

Fig. 5: Validation of the model of the innovative cold district heating network by comparison with analytical calculation results

In a second step the simulation results of the model including the effects by solar and thermal radiation and the heat exchange with the ambient air were calculated and are also shown in Figure 5 as a dashed grey line. In comparison to the simulation results without these effects and the analytical calculation the heat gains are mostly in the summer months higher. This is plausible as these are usually months with higher heat gains through solar radiation and hence higher earth temperatures in the area of the pipe. This also shows the noticeable dependency of the heat gains and losses from impacts originating from the surface as the pipes of cold district heating networks are usually buried in a low depth of 1 to 2 m below the surface.

Overall, the comparison with the analytical calculation results shows that the simulation results by the model can be considered as valid with a high probability. To further support this assumption, an additional validation of the simulation model with measurement values of a real pilot plant of a cold district heating network is planned. Based on the results of that comparison with measurement values the configuration and if necessary, the programming of the model will be improved with the goal to model the heat gains and losses of a cold district heating network even more accurately.

8. Comparison of the innovative with a conventional cold district heating network

The cold district heating network is an essential part of the entire cold district heating system, as it connects the different components exchanging heat with the consumers to cover the heating or cooling demand. The change of the heat transfer medium from a mixture of water and antifreeze to only water has an effect on the fluid temperatures in the network and therefore on the heat gains and losses of the cold district heating network. The results of some investigations regarding these effects are described in this chapter.

Those investigations are based on system simulations performed with the developed simulation model described in chapter 5. For this purpose, both for the conventional and the innovative cold district heating system an adapted simulation model has been created. Additionally, both simulation models have the same boundary conditions based on a newly built district completed in May 2022. This district is located in the city of Ludwigsburg, about 15 km north of Stuttgart and therefore influenced by continental climate. It consists of nine multi-family houses and a kindergarten with three residential units above. In total, for the 107 residential units with a heated floor space of 8,567 m^2 an annual heating demand of 508 MWh and a cooling demand of 167 MWh is assumed. The supply of domestic hot water is not taken into account, as domestic hot water is provided by electric instantaneous water heaters. For the cold district heating network pipes with a length of 420 m each for flow and return and with the dimensions and material properties described in chapter 7 are used. Just like in the validation in chapter 7 those pipes are equipped with an insulation.

In Figure 6 the average inlet temperatures in the flow pipe and the return pipe of the cold district heating network are shown. In addition, the monthly heat gains of the cold district heating network through heat transfer from the surrounding earth are shown as positive bars and the heat losses as negative bars.

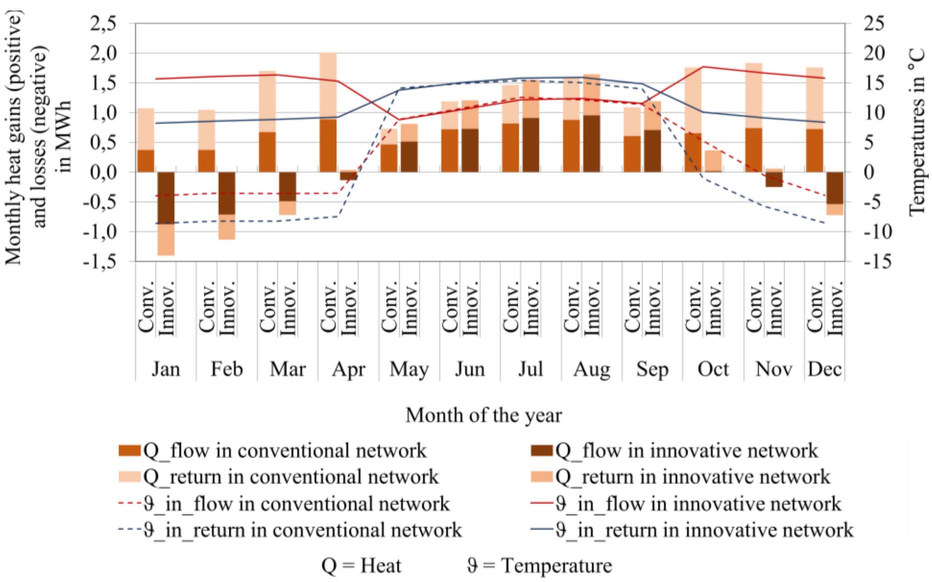

Fig. 6: Comparison between the conventional and innovative cold district heating network regarding temperatures and heat gains or losses respectively in the cold district heating network

Firstly, the average inlet temperatures of the innovative cold district heating network are significantly higher in the months with heat demand, compared to the temperatures of the conventional system. This can be explained by the additional central heat pump that is necessary to increase the temperatures for the usage of water as heat transfer medium. Due to the partly negative outlet temperatures of the solar thermal air-brine-collectors and the ice store the temperatures in the cold district heating network of the conventional system are accordingly below the freezing point during most of the time in the heating season.

Secondly, as a result of the higher temperatures in the innovative cold district heating network compared to the surrounding earth, heat losses occur from November to April. In contrast, there are heat gains in the conventional cold district heating network due to lower temperatures compared to the surrounding earth temperature. In relation to the overall heat supplied to the buildings there are significant heat gains in the conventional cold district heating network, in contrast to the low heat losses in the innovative network in the months with heating demand (as shown in table 1). In the months with cooling demand both the conventional and the innovative network have similar heat gains in relation to the overall heat removed from the buildings.

Tab. 1: Comparison of the heat gains and losses of the conventional and the innovative cold district heating network in relation to heat supplied and removed from the buildings

		Conventional	**Innovative**
Months with heating demand Oktober until April	Heat supplied to the buildings	507.7 MWh	507.7 MWh
	Heat gains or losses	11.2 MWh 2.2 % heat gains	3.9 MWh 0.8 % heat losses
Months with cooling demand May until September	Heat removed from the buildings	163.3 MWh	164.6 MWh
	Heat gains	6.1 MWh 3.7 % heat gains	6.4 MWh 3.9 % heat gains

Generally, heat gains in the months with heating demand can be rated positive as they can reduce the heat supplied by the ice store and therefore preserve its state of charge. Heat gains in the months with cooling demand are negative as they require additional electricity to remove the heat gains from the network.

In relation to the innovative cold district heating network the goal of the ongoing research project “SolKaN2.0” is to minimize the heat losses in the months with heating demand or even reach heat gains in those months. One approach to accomplish this goal is to reduce the fluid temperature in the network as much as possible by means of an optimized control of the central heat pump and the decentral heat pumps in the buildings. As shown in Figure 2 the average inlet temperatures in the flow and return pipes vary between 8 and 18 °C in the months with heating demand. As a minimal temperature of 3 °C is sufficient to avoid freezing of the water this offers a high potential for temperature reductions. Another approach is the use of a thermal insulation with a lower heat transfer coefficient or the insertion of the pipes at a greater depth below the surface. These measures would also decrease the heat gains in the months with cooling demand and therefore increase the efficiency of the system during periods with cooling demand.

9. Conclusion and outlook

In the research project “SolKaN2.0”, which started at the beginning of the year 2024, the development and implementation of a new generation of cold district heating systems with water as heat transfer medium in the cold district heating network is performed. The mainly ecological and economic reasons for changing the heat transfer medium from a mixture of water and antifreeze, which is commonly used in conventional cold district heating systems so far, to water were presented at the beginning of this paper. After that a concept of an energy supply system covering heating and cooling demands with the innovative aspect of water as heat transfer medium in the cold district heating network was introduced. To realize this innovative system an additional central heat pump between the thermal energy sources and the cold district heating network is necessary.

In addition, as part of this research project, a simulation model for this innovative system was developed and the resulting simulation results were used to perform various investigations. For this paper monthly heat balances and the state of charge of the ice store over the period of one year were calculated and presented. Thereby the essential role of the ice store as a seasonal thermal energy store integrated in the cold district heating system was shown.

Besides the ice store the cold district heating network has been examined theoretically in more detail. Therefore, in a first step the used simulation model for the network was validated with analytical calculation results. In a second step numerical system simulations of a conventional and an innovative cold district heating network were carried out. The results showed higher heat losses in months with heating demand as a result of the higher fluid temperatures in the innovative network compared to a conventional network. As the reduction of those heat losses is one goal of the ongoing research project, ideas to achieve this were presented at the end.

In conclusion, although the heat losses in the cold district heating network can be rated negatively, it is expected that the ecological and economic advantages using water as heat transfer medium outweigh potential higher heat losses. The development and implementation of a new generation of cold district heating systems with water as heat transfer medium and to proof the functionality and advantages of this new innovative system concept is the central goal of the research project “SolKaN2.0”. In this context also a prototype of the central heat pump will be developed and tested together with a small ice store at the IGTE in Stuttgart in a first step. In a second step a pilot plant of the whole new innovative cold district heating system will be implemented in a real district in Germany and assessed technically, economically and with regard to environmental aspects based on detailed measurement data.

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