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# 6$^{th}$ Generation District Heating and Cooling Networks: Design, Experimental Results and Future Challenges

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**Abstract.** This paper describes the design and testing of an innovative lab-sized 6$^{th}$ generation district heating and cooling network (6GDHCN) using $CO_2$ as heat transfer fluid to evaluate its simultaneous heating and cooling capabilities and highlight current design challenges and future pathways to enhance the system. The 6GDHCN distinguish from its predecessor by the use of phase change phenomena to transfer heat. The innovative use of phase change significantly enhances energy density, thus enabling smaller infrastructure requirements and simpler deployment in dense urban environments. The experimental setup, developed to emulate real-world conditions on a reduced scale, includes a central plant circulating $CO_2$ through network connecting cooling and heating users. Experiments focused on validating the concept and the correct operation of each subsystem as well that of the overall facility. Similarities with a larger facility provided a solid basis of demonstration of the emulation capabilities. In particular, the experiments allowed to identify the major design challenges and identify pathways for enhancing system resilience, scalability, and energy efficiency in sustainable thermal networks.

**Keywords:** energy; district; heating; cooling; network; $CO_2$; phase-change; construction; environment; sustainability

## 1 Introduction

Thermal energy distribution networks are key components of territorial energy systems. These have evolved through different generations to meet technical and energy needs characterising their time period. Despite five successive generations of technological advancements, the fundamental principle — circulating a single-phase fluid with sensible heat exchange — has remained unchanged.

The main characteristic of the first heat distribution network, dating back to the 14$^{th}$ century [9], remained unchanged for four technological generations (i.e. from 1GDHN to 4GDHN): energy-heat production distributed by a single-phase fluid with a significant temperature difference from the environment. This system is characterized by a single service (heating or cooling), fixed producer and consumer roles (no interaction), high temperature differences between the fluid and the environment (losses), and medium energy density (large piping). The evolution between different generations of networks is characterised by a decrease of their operating temperature, decreasing the heat losses and therefore, increasing the efficiency and the potential for integrating renewables. Alternatively, the 5GDHCN (or "aenergie network") circulates a low temperature fluid, typically water, that serves as cold source for heat pumps and chillers. Lowering the network temperature reduces thermal losses but decreases energy density, which is offset by increasing the mass flow and consequently, increasing the pipe diameter (to reduce the friction losses). This makes the network less suitable for urban areas where underground space is constrained and large construction works significantly impact local citizens (e.g. noise, dust, traffic management) and economy.

To address these, a 6GDHCN has been developed. This network uses a fluid in liquid and vapor phases (i.e., a two-phase system) that leverages the enthalpy of vaporization and condensation for heat exchange. This system combines the advantages of all previous generations with phase-change, exploiting a higher energy density and therefore using smaller diameter pipes, making it simpler to deploy. However, it also introduces challenges, particularly in managing phase-change, operating mode transitions and operating pressure. Furthermore, notable research gap remains in demonstrating the operational viability and control strategies required for phase-change networks under realistic multi-user conditions.

The potential of 6GDHCN using $CO_2$ concept was firstly studied by Weber and Favrat [8], where they demonstrated that it is both energetically and financially more advantageous than an equivalent water-based network. Other fluids have been considered by Henchoz [3], but $CO_2$ was shown to be best option. The concept was theoretically analysed in different studies ([2, 4, 7]).

The feasibility of this technology was partially demonstrated with a scaled-down $CO_2$ network [3] consisting of a central plant connected to a single user, a cooling user (i.e. user to be cooled, thus, evaporating $CO_2$ liquid). However, in a practical scenario, such a network would consist of various users, each interacting with the network differently. In this context, two projects 6GDHCN were studied: one in Sion at the Energypolis site, where a network supplies three buildings, and the other in Geneva at the Fusterie site (city center), designed to interact with the GENILAC network (a 5GDHCN). Despite these studies, this remains a recent technology, for which there is no numerical model or physical facility capable of replicating the operation of a real-world case. It is in this scope that ROADMAP [5] research project has been developed: develop a physical test section and a numerical model allowing to emulate and simulate, respectively, the 6GDHCN. This paper focus on the design and testing of an innovative lab-sized 6GDHCN, that includes both heating and cooling users, to evaluate its simultaneous heating and cooling capabilities and highlight current design challenges and future pathways to enhance the system.

## 2 6GDHCN Principle

The 6GDHCN – or $CO_2$ network – is a recent technology that differs from 5GDHCN, by the use of liquid and vapor phases to convey heat, taking advantage of phase-change (evaporation and condensation) for transferring heat. The operating principle of the $CO_2$ network is schematically illustrated in Fig. 1. It consists of two pipelines at very close temperatures and pressures: one transporting vapor and the other one transporting liquid. Heat transfer between the network and each user is achieved almost exclusively by leveraging the latent heat associated with the phase change of the working fluid. A cooling user transfers heat to the network by evaporating $CO_2$ drawn from the liquid pipeline and introducing the resulting vapor into the vapor pipeline. A heating user operates inversely. The balance between consumers may or may not be zero; therefore, a central station is required. In Fig. 1, the central plant is equipped with a cold source and a compressor, but other configurations are possible. In this setup, the compressor is used solely to slightly superheat the vapor. The figure illustrates two users: the first consumes cold energy through "free cooling," while the second consumes hot energy using a decentralized heat pump. When the network is overall in surplus of hot energy (i.e. deficit of cold), excess thermal energy is released into a cold source, such as a lake, through the condensation of vapor, which is then injected into the liquid pipeline (Fig. 1(A)). Conversely, when the network is in deficit of heat, the reverse process is performed (Fig. 1(B)).

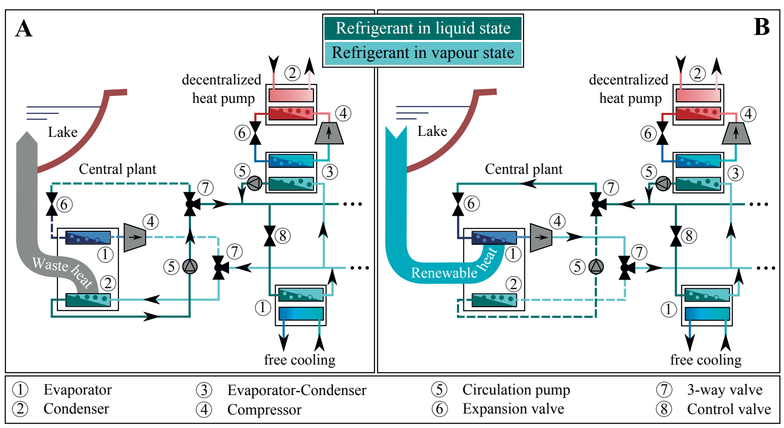


Fig. 1: Schematic representation of a refrigerant based district energy network for two cases, (a) net cooling operation and (b) net heating operation [3]

## 3 6GDHCN Facility Design

Based on the objectives and on a previous design [3], the system was upgraded with many improvements, in particular, a heating user as shown on the schematic in Fig. 2 and accordingly to the characteristics listed in Table 1. The operating parameters regarding the new heating user were selected based on optimal balance between thermodynamic efficiency, material constraints, and system safety margins, informed by preliminary calculations.

The central plant regulates the $CO_2$ operational conditions in function of the network status (i.e. users demand). The plant is equipped with a variable-flow pump and a heat exchanger that can be used as evaporator or condenser. In particular, it can automatically shift between heating or cooling modes, depending on the overall network demand. The vapor and liquid lines - 7/8" and 3/4" heavily insulated copper tubes, respectively - operate in superheated (15°C and 50 bar) and subcooled (13°C and 52 bar) conditions, respectively. The cooling user consists of a $CO_2$ evaporator where the mass flow is controlled via a superheat of 3 K. The heating user consists of a $CO_2$ condenser, liquid reservoir and variable-flow pump, where the mass flow is controlled via a subcooling of 3 K.

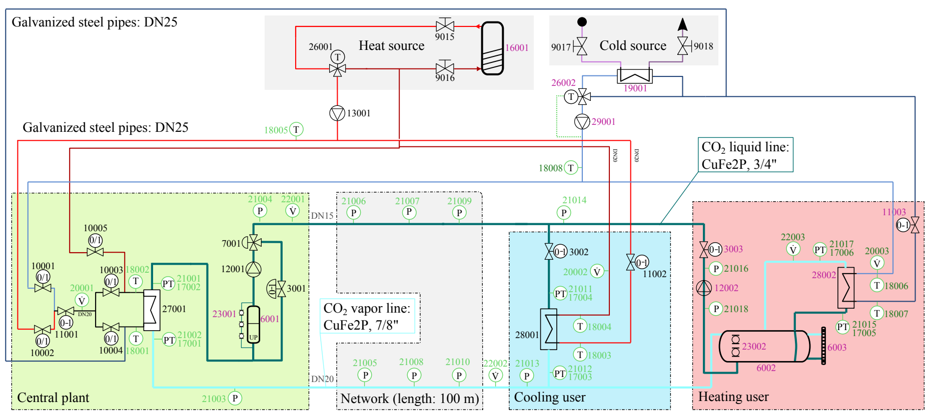


Fig. 2: ROADMAP project 6GDHCN experimental facility schematic. Certain details are intentionally omitted for IP protection purposes

The experimental facility, originally developed by Henchoz [2], underwent significant modifications in order to meet the new design specifications. Besides upgrading the central plant and adding the cooling user (condenser, reservoir and pump, control valves, security components, instrumentation and control), the modifications included enhanced and additional instrumentation, additional safety mechanisms, new heat and cold sources and respective hydraulics, a massive update of the $CO_2$ ducts and regulation and control software. The resulting experimental facility is depicted in Fig. 3.

## 4 Experimental Results

An extensive experimental campaign has been undertaken to validate the correct operation of each subsystem (central plant, cooling user, heating users, security, measurement, data acquisition and control), as well of the correct operation of the overall facility. The results validated each one of the items and furthermore, have proven that the concept is fully functional. The data is open source and freely available [1].

Table 1: ROADMAP project 6GDHCN experimental facility characteristics

| Section | Parameter | Value | Unit / Notes |
|---|---|---|---|
| Generalities | Network pipe length | 2 x 100 | m |
| | Total fluid volume | 175 | Lt |
| | Max. $CO_2$ pressure | 64 | bar |
| | Dimensions | 2.5 x 2.5 x 5.5 | m (H x W x D) |
| Nominal operating conditions | $CO_2$ mass | 90.3 | kg |
| | $CO_2$ saturation pressure | 50 | bar |
| | $CO_2$ saturation temperature | 14.2 | °C |
| | Hot water source temp. | 40 | °C |
| | Cold water source temp. | 8 | °C |
| Liquid line | Temperature | 13 | °C |
| | Pressure | 52 | bar |
| | Diameter | 3/4" | (19 mm) |
| | Volume | 34.6 (17.7) | Lt |
| | Mass | 29.2 (14.6) | kg |
| Vapor line | Temperature | 15 | °C |
| | Pressure | 50 | bar |
| | Diameter | 7/8" | (19 mm) |
| | Volume | 35.4 (31.4) | Lt |
| | Mass | 5.3 (4.9) | kg |
| Main plant | Power | 26 | kW |
| | $CO_2$ flow rate | 134 | g/s |
| | Hot water flow rate | 260 | g/s (0.94 $m^3/h$) |
| | Cold water flow rate | 2074 | g/s (7.47 $m^3/h$) |
| | Control | $\Delta P$ between liquid and vapor line: 2 bar | |
| Cooling user | Power | 13 | kW |
| | $CO_2$ flow rate | 67 | g/s |
| | Hot water flow rate | 130 | g/s (0.47 $m^3/h$) |
| | Control | Superheat at evaporator outlet: 3 K | |
| Heating user | Power | 13 | kW |
| | Hot water flow rate | 67 | g/s |
| | Cold water flow rate | 1037 | g/s (3.73 $m^3/h$) |
| | Control | Subcooling at condenser outlet: 3 K | |

The results [5] have clearly shown trends similar to those observed within the larger facility of Energypolis [6]. The observed similarities provide a solid basis of demonstration of the emulation capabilities of this experimental facility.

Among the different tests, the one covering the automatic shift between heating and cooling modes of the central plant was selected. Figure 4 depicts the $CO_2$ pressures (numeric code indicates the measurement instruments in Fig. 2) at different locations of the facility: the $CO_2$ mass flow rates in the liquid and vapor lines and in the heating user, the hot and cold water volumetric flows at the central plant and users and finally, the enthalpy variation of water – or the thermal power exchanged – at the central plant and by users, all in function of time (in minutes). At the beginning of the test, only the cooling user is active. At about 5 minutes, its demand is gradually reduced by reducing its hot water mass flow, until full stop. During that process, the $CO_2$ mass flows in the liquid and vapor lines clearly follow the same trend. At about 6 minutes, the heating user is engaged and its demand gradually increased (see its water flow increase). The network overall heat demand is shifted from heating to cooling, forcing the

Fig. 3: ROADMAP project 6GDHCN experimental facility

central plant to shift from heating to cooling mode with the liquid and vapor mass flows direction shifting in their respective lines. This heating mode transition noticeable impacts the $CO_2$ pressure in the network. Indeed, during the transition the central plant is stopped and not equilibrating the network. After about 5 minutes, the system reaches steady state again.

Thanks to the experimental campaign, it was possible to identify the major design challenge: dynamic flow control. At start-up or at user load variations, the system has shown to undergo transients that have to be correctly addressed. Within this project, the dynamic control parameters were empirically set for each experimental condition, and therefore not optimised. Oscillatory trends were observed, sometimes leading to undesirable effects such as central plant's pump dryout. The challenges related to the dynamic flow control concern both central plant and users, for which subcooling and superheat have to be precisely controlled to avoid instabilities.

## 5 Conclusions

This study successfully demonstrated the feasibility and operational viability of a lab-scale $CO_2$ based 6GDHCN, highlighting its potential for real-world urban deployment. Critical insights were gained into dynamic control challenges, providing a clear pathway for future system enhancements.

The present study allowed to design, build and test an innovative lab sized $CO_2$ based 6GDHCN. The experimental facility incorporates a cooling and a heating users of 13 kW each, within a network of 100 m long, allowing to emulate real-world cases in particular, study and characterize the behavior of a study case network under specific operating conditions. The main features of this experimental facility are its modularity and flexibility. In terms of modularity, it can be easily modified to add/modify users or any other component/hardware. In terms of flexibility, its operating conditions can be quickly set/modified to

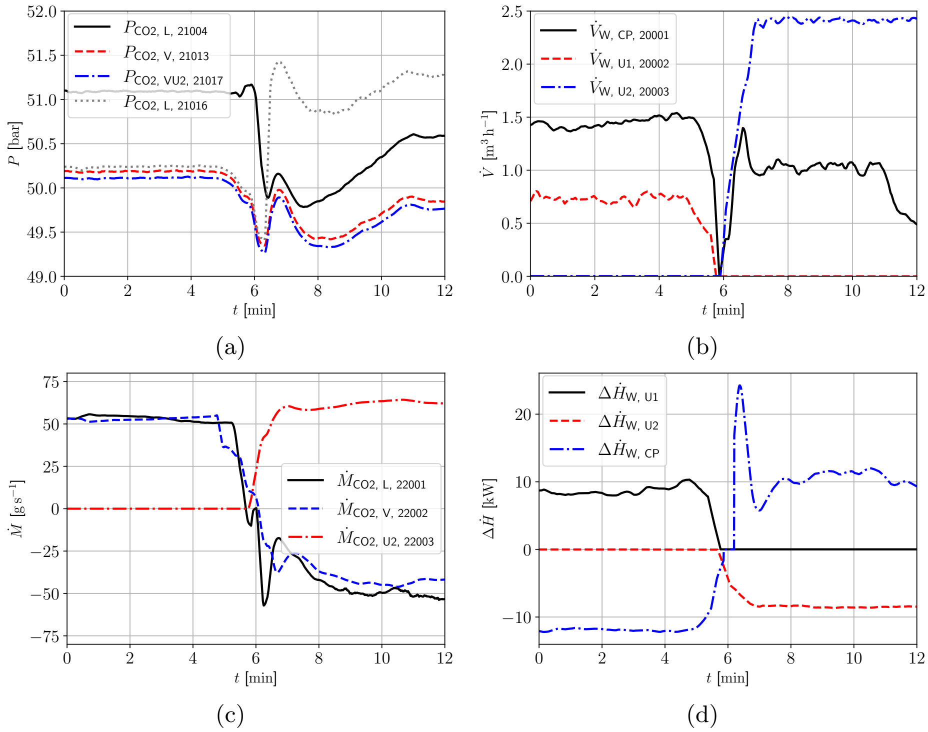


Fig. 4: Experimental results of (a) pressures, (b) water mass flows, (c) $CO_2$ mass flows rate and (d) enthalpy variation of water (thermal power), during central plant shift between cooling and heating modes.

emulate a real/study-case network under different experimental conditions (e.g. extreme stochastic loads). Furthermore, the experimental facility also allows to quickly deploy and test regulation/control strategies.

Experiments focused on the validation of the design and operation of the different subsystems (central plant, cooling and heating users, security, measurement instrumentation, data acquisition and control). The experiments validated the design and operation of the system. Most of all, they have shown that the concept is fully functional, i.e. it is possible to successful operate a phase-change latent heat based DHCN. Results have also shown trends similar to those observed with a larger facility, therefore providing a solid basis of demonstration of the emulation capabilities.

Future research should prioritize addressing specific technological hurdles such as dynamic control under transient conditions and integrating advanced predictive algorithms for enhanced operational stability. To mitigate instabilities during central's plant mode shifting, heating and cooling systems should be separated. This would also contribute for effective scalability and resiliance, ensuring robust performance and efficiency at larger scales.

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