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Novel district heating and cooling energy network using CO_2 as a heat and mass transfer fluid

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Abstract

Compact district energy networks in a temperature range of 10 to 16°C have a great potential for energy savings by providing a heat source for decentralized heating heat pumps, a cold source for air-conditioning and a heat sink for refrigeration or cogeneration units. The energy balance of the network is done by a central plant equipped with a heating heat pump for Winter operation and a heat dissipater for Summer operation. They typically facilitate the synergy between users and allow the concept of a city without chimneys or cooling towers in the various buildings. One such concept is based on using the latent heat of the transfer fluid (CO_2), with one saturated CO_2 vapor pipe and one saturated CO_2 liquid pipe, in which the flow is bidirectional depending on the predominance of either heating or cooling demands. While the concept has already been published this paper discusses some of the potential dynamic phenomena as well as further extension to allow those networks to collect CO_2 from hybrid decentralized SOFC-GT cogeneration systems for either further disposal, use or contribution to power to gas concepts. Additional extensions to using reversible supercritical CO_2 heat pump or ORC is also mentioned. A reminder of the technico-economic results obtained on the actual demands of an existing district is also done including the evaluation of the uncertainty margins

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District heating, cooling, smart energy cities, CO_2 transfert fluid, centralized and decentralized heat pumps, storage

1. Introduction

Since a growing part of the population worldwide will live in cities, urban energy supply is very important when considering improved energy efficiency strategies. However, as a result of the different willingness of

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building owners to invest in the energy renovation of their buildings, the building stock is often very diverse. This results in the fact that the energy demand and the required temperature levels for each building tend to differ within a given part of a city. Moreover cooling loads tend to increase in central city district with a large share of shops and offices including data centers. Hence a growing implementation of both heating and cooling networks in already crowded city undergrounds. To face the temperature heterogeneity of building requirements, concepts of medium to low temperature district heating (DH) systems, with or without decentralized heat pumps, have been proposed and implemented [1,2,3]. Other concepts combine heating and cooling (DHC) supply in very low temperature networks where the transfer fluid acts as cold network for cooling purposes and supplies evaporator heat to decentralized heat pumps heating the different buildings. Those have the advantage of better efficiency since the individual heat pumps supply just the temperature level needs of the individual buildings and they consist of a 2 pipe rather than a 4 pipe system. However, to limit the exergy losses and since they are only based on the specific heat of water, they need to have a reduced difference of temperature between the supply and return pipes (down to a few degrees) implying the transport of large amounts of water and therefore large pipes and trench requirements. This paper complete a series of papers [4,5] on an alternative concept of significantly more compact, very low temperature network using the latent heat of CO_2 that is used both as a refrigerant and an energy transfer fluid. Furthermore CO_2 does not have a risk of freezing and, therefore, street implantation does not require any significant depth for freezing protection in case of trouble. Like the very low temperature DHC heating and cooling networks based on water and since the temperature level is closed to that of the surrounding ground, insulation can be reduced to minimum allowing a further gain in ditch width requirements. Furthermore the temperature level corresponds to ground vertical probes for thermal storage or geothermal heat capture. Several other alternatives of use of such networks are described in the next sections. Note that here the terminology of very low temperature DHC is used not to confuse with the so-called low temperature of the 4th generation review defined in [6, Table 1]

2. Description of the proposed DHC

Figure 1a and 1b illustrate the network with the central plant and the first users in summer and in winter. The network consists of one saturated liquid pipe and of one saturated vapor pipe both in a saturated temperature range of 10 to 16°C. In summer, free cooling is provided for air conditioning by evaporating liquid taken from the liquid pipe and releasing it in the form of vapor to the vapor pipe. In winter, vapor is taken out of the vapor pipe, condensed in a condenser-evaporator of the cold side of a heat pump and then released in the liquid pipe. Direct use of the CO_2 is also an option particularly for hot water heating in which case vapor is compressed in an oil-free compressor before being cooled in a countercurrent domestic water–refrigerant cooler. Overall this implies that the flow in the pipes can go in both directions depending on the relative ratio between cooling and heating duties, and a central plant balances the loads. Ideally the central plant is closed to superficial water (lake, sea, river). If no water is available at the central plant, a field of geothermal probes might do the job. To prevent filling up the pipes or geothermal probes with oil, oil-free compressors or at least compressors equipped with excellent oil separators are required [like in 7].

Because of the very low temperature of this system a real synergy between heat providers and heat users can be achieved. For example, the condenser heat from refrigeration units can be recycled, via a decentralized heat pump, to satisfy heating needs elsewhere. This is in contrast to the present situation, seeing side by side the cooling tower of a shop and the chimney of a fuel based hot water heater. It is a step towards future districts without chimneys or cooling towers. A recent theoretical study on a real district in Geneva shows that more than 80% of the energy could be saved, compared to today's energy system using predominantly fuel boilers and conventional single stage refrigeration and air-conditioning units [4]. The actual heat and cold demands of this particular district are shown in Figure 2. This figure shows that, except for server cooling and refrigeration services, the overlap is rather limited in this particular district but, in spite of that, the energy savings are

considerable. In addition, the size of piping is significantly reduced, as shown in Figure 3, to the point that the pipes could be disposed in utility channels in pedestrian paths for example, as shown on the right of the figure. The relative dimensions account for CO_2 safety pipes with a double envelop as shown at the bottom right part of the figure.

The main drawback is the high pressure of the order of 50 bars and the large inventory of CO_2 that could cause some safety concerns in case of a major leak. However several hundreds of supermarkets in Europe [8] are already equipped with direct CO_2 networks supplying cold at slightly lower pressures of the order of 40 bars with safety valves calibrated at 70 bars.

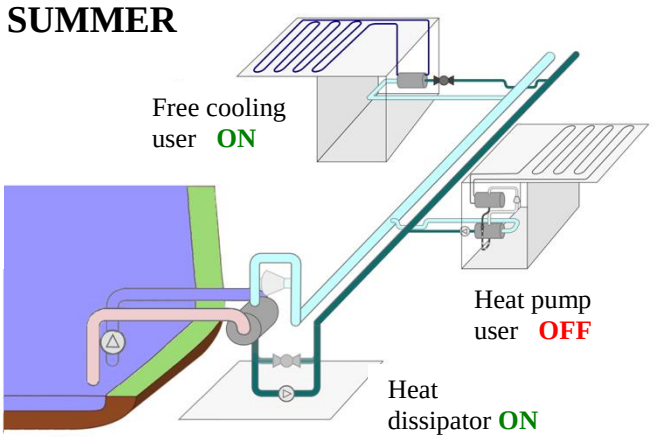


Fig. 1a. Central plant and first users in **summer** of a CO_2 based DHC

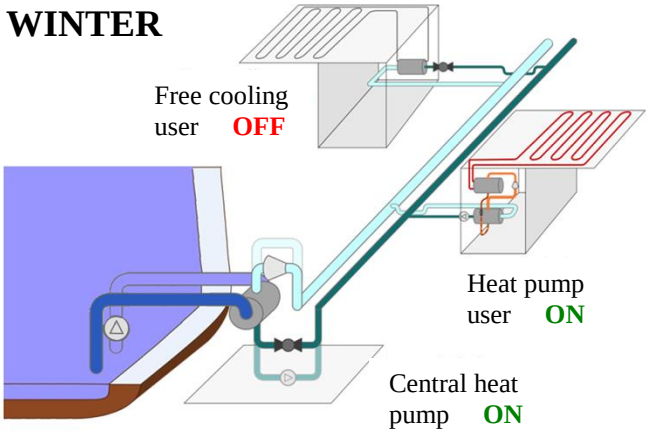


Fig. 1b. Central plant and first users in **winter** of a CO_2 based DHC

Figure 4 shows one concept of safety measure with fast closing valves, piloted by an excessive depressurization in a control venturi. The use of CO_2 as natural refrigerant has many advantages. It is inert and compatible with both metals and plastics or elastomers, non-flammable, non-toxic, cheap and abundant in the environment, therefore requiring no recovery or recycling. It also possesses a high volumetric thermal capacity.

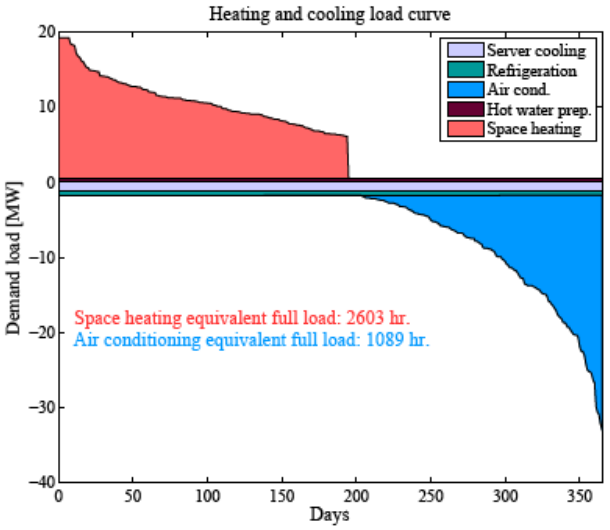


Fig. 2. Heating and cooling loads of the chosen district

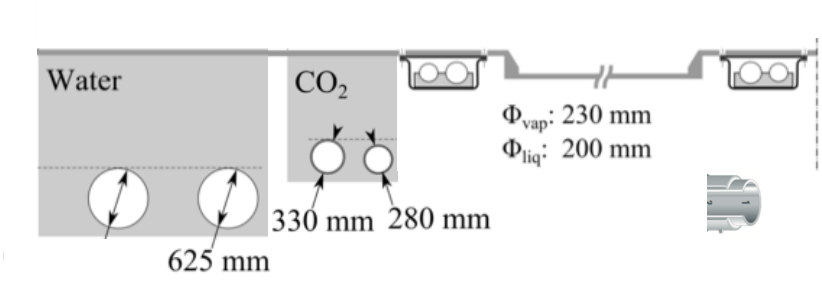


Fig. 3. Size comparison between a water-based and a CO_2-based very low temperature DHC

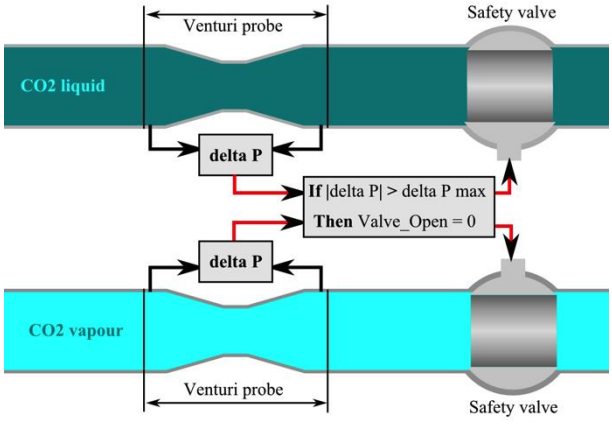


Fig. 4. Example of safety measure to reduce CO_2 spill in case of a major leak

However its use raises safety issues, since it is colorless and odorless, and can asphyxiate at strong concentrations. Of course, the fairly high operating pressures makes it more hazardous and increases the leak potential.

According to the safety group classifications SN EN 378-1:2008+A2: 2012 [9], CO_2 is in the group A1, in which toxicity (A) has not been identified at concentrations less than or equal to 400 ppm and flammability (1) of course does not show flame propagation. According to the PED directive 2014/68/EU, CO_2 is a group 2 fluid (not explosive, nor flammable, nor toxic or oxidizing).

According to NIOSH [10], OSHA [11], CGIH (American Conference of Governmental Safety and Health Administration), HSE [12], the threshold limit Values (TLV) and the Permissible Exposure Limit (PEL) for CO_2 is 5000 ppm (0.5%). The immediately dangerous to Life and Health Limit (IDLH) is considered generally at 50000 ppm (5%), but a more restrictive value of 15000 ppm is given by HSE [12]. For more information including standards in different working environment see [13]. Sensors along the network and in the energy room of each building are being proposed.

When it comes to corrosion, recommendation is done to use dryers on the way to prevent a CO_2-water mixtures to attack the piping.

One particular fear is linked to the so-called Boiling Liquid Expanding Vapor Explosion (BLEVE) regarding a sudden rupture of the saturated liquid pipe. This would result in rapid pressure reduction causing a nearly instantaneous transition from liquid to vapor with a corresponding energy release. Such a phenomenon is likely to occur if the liquid is initially at a pressure high enough for the superheated liquid to reach the spinodal point during depressurization. However, no such phenomenon has been observed in supercritical heat pumps or refrigeration units. It seems that high pressure liquid pipelines are much less susceptible to end up in a BLEVE than in the case of spherical storage. This could be explained by the large source of nucleation sites on the rough surface of the pipes, making the boiling process to start earlier, thus reducing the risk of explosive boiling.

The risk linked with the potential breakage of a component containing CO_2 in the gaseous phase seems not to be of greater concern than its liquid counterpart. Various caution measures are described in [13].

3. Experimental proof of concept

A scaled down lab facility was built to have a proof of concept to demonstrate the feasibility using only existing components, with scalable results and in which the potential hydro-acoustic phenomena could be observed and measured. Furthermore the test rig was to allow for the experimentation of various control schemes.

Both the liquid and the vapor lines are 100 meters long with 20 u-bends organized in 3 levels each to obtain a compact setup as can be seen in figure 5 (number 4 and 5). The diameters of the pipes were ¾''for liquid and 7/8'' for vapor.

The first phase of the test was to simulate a cooling user with a plate heat exchanger, in which CO_2 from the liquid line is evaporated while water is cooled down, like it would be at an air-conditioning user. Similarly a simulated central plant, at the other end of the network, is already built to work in both cooling and heating modes to balance the pressures and energy in the network. The simulated central plant consists of a CO_2-water plate heat exchanger, fed on the water side from the building hot water network at a temperature between 55 and 60°C, and the building chilled water network at a temperature varying between 8 and 11°C. Mixing valves are used to reproduce the typical temperatures of a real network. The central plant heat exchanger acts as a CO_2 condenser, when the rig is operated in cooling mode, and as a CO_2 evaporator when the rig is to be operated in heating mode. The cooling user is also connected to the heat source. The booster pump, as indicated in Figure 5, was necessary to achieve a sufficient mass flow on the cold water supply of the central plant. As mentioned above a key purpose of the tests was to assess the dynamic behavior and the controllability.



1: Cold source supply manifold	4: Vapour main line
2: Booster pump (29001)	5: Liquid main line
3: Cooling user	6: Compressed air supply

Fig. 5. Picture of the test rig installed at the industrial energy services in Geneva

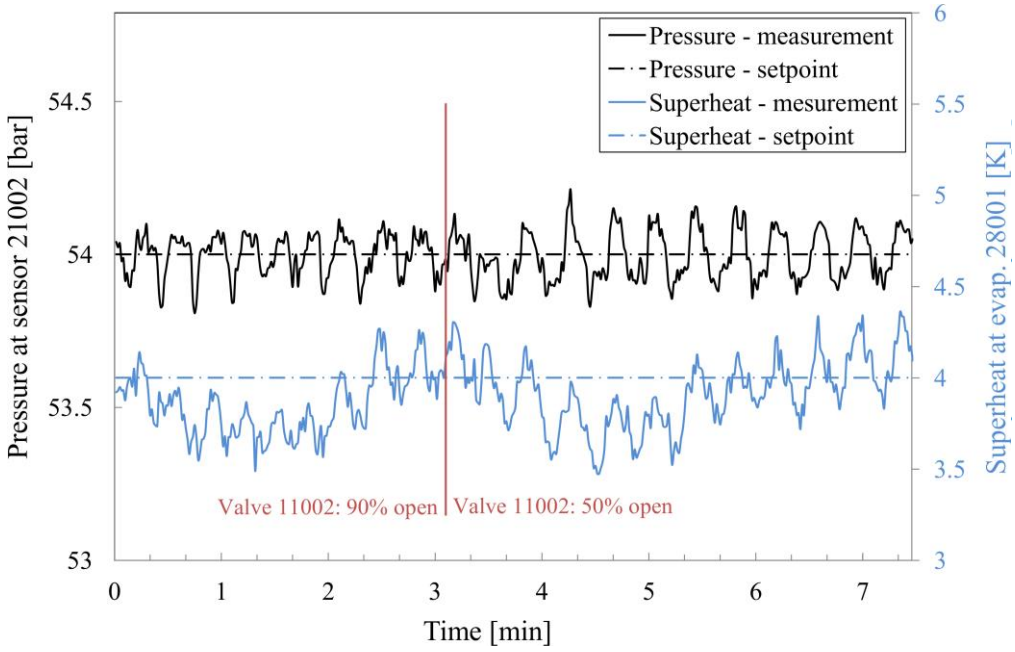


Fig. 6. Example of the control achieved on the pressure in steady operation (before time 3.1min) and following a sudden reduction at 3.1 minutes of the evaporator load at the user of 45%

Among the dynamic phenomena, it was important to verify the absence of abrupt changes of pressure that could be a threat to the reliability of such a refrigerant-based network. The first successful tests aimed at demonstrating that the chosen concept of automatic control was adequate for most of the steady points tested. Some small pressure fluctuations and evaporator superheat were observed, as seen in Figure 6 at steady state before time 3.1 minutes. At that time, a step change in the opening valve of the water flow at the user heat exchanger was introduced corresponding to a load reduction of about 45%. As can be seen, the effect of the load reduction is small and the only noticeable change is a slight increase of the amplitude in the pressure fluctuations. Notice that the load step change did not cause any significant superheat excursion.

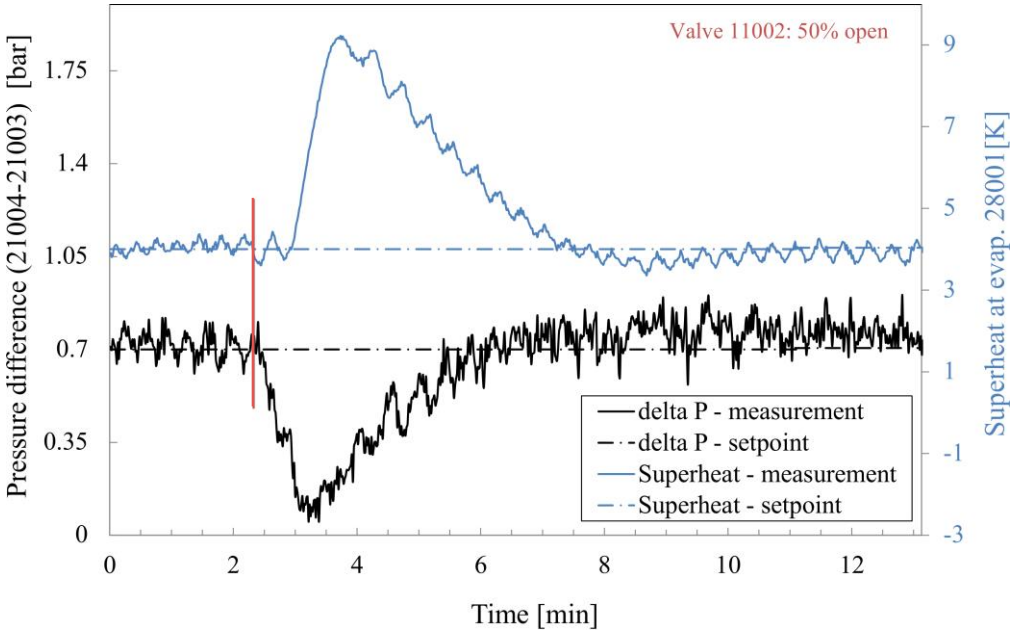


Fig. 7. Control achieved on the pressure difference between the liquid and vapor lines and on the superheat at the outlet of the evaporator following a step change in the set point from 50 to 52 bar (taking place at the red bar)

Another test was to produce a step change in the set point of the PI pressure controller from 50 to 52 bar. In a real CO_2 based district heating and cooling network such sharp changes in the pressure set point would not be used. However, in the test rig context, step changes allow for a clear view of the effects and potentially visualize dramatic pressure phenomena if the risk was important. The test results on the pressure difference between the two pipes, as well as the effect on the superheat at the evaporator outlet, are shown in Figure 7. First, it can be seen that the pressure takes 40 seconds to reach the new set point. For the rest of the duration of the test, the pressure is maintained at the 52 bar set point (within the usual fluctuations). The superheat is much more strongly affected by the step change, since a large excursion occurs from 45 seconds after the step change and lasts for more than 4 minutes.

A ramp downward change of the pressure level from 58 to 54 bar was also tested. The pressure reduction ramp was of 4 bar in 2 minutes, as can be seen in figure 8. A striking effect is a pressure excursion at the end of the ramp while the superheat remains under control for the duration of the ramp. The inability for the system's pressure to follow the prescribed path is due to the flooding of the condenser with liquid. In fact, once this happens, the pressure cannot continue to decrease, that results in the saturation of the controller and the command of the cooling water valve remains fully open.

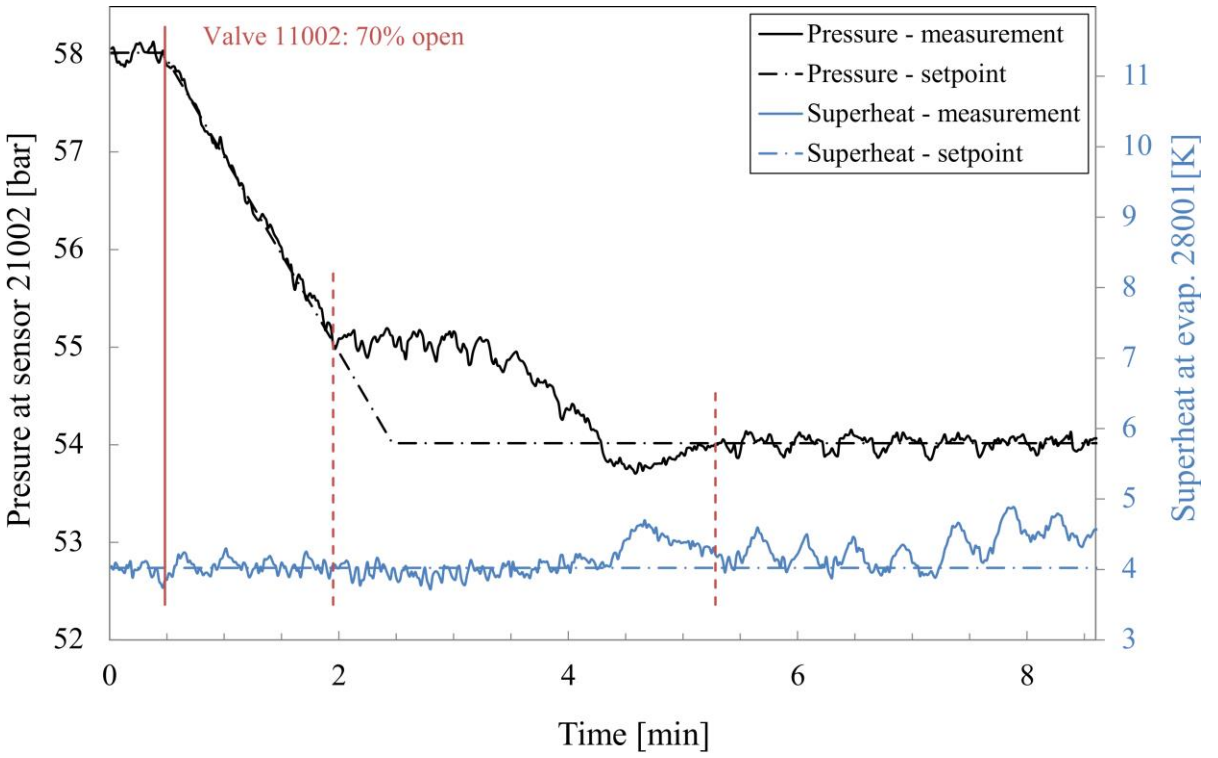


Fig. 8. Control achieved on the pressure at the condenser inlet and on the superheat at the outlet of the evaporator following a change in the set point from 58 to 54 bar in a 2 minute ramp

Experiments done so far did not indicate any major pressure excursion and showed that the control of such a novel network could be achieved within reasonable limits.

Another experiment done was to try to induce "water hammer" like phenomena by abruptly closing one of the sectioning valve of the network when the system was operated at high load (26.3 kW). The rapid stopping of a fluid in a pipe can cause a series of pressure waves travelling back and forth, in particular when the velocity is high and the fluid relatively non compressible. This phenomenon is well known in hydropower pipes, where it puts constraints on the minimum time for the main valves to close so that very high and very low pressures can be avoided. The liquid hammer test consisted in operating the test bench at the highest achievable load, by feeding the user with water at the temperature provided by the heat source (60°C). It led to a pressure in the network of 53 bar and a mass-flow of CO_2 of 0.14 kg/s. After stabilization, one of the sectioning valves was closed. These conditions were expected to lead to the worst liquid hammer that could be induced in the test bench. The result is shown in Figure 9. The positive pressure spike starts 0.2 s at 33 meter along the pipe, 0.4 s at 67m and 0.6 s. at 100m. This corresponds to a traveling wave velocity of around 170 m/s, a value about half of the sound velocity of CO_2, that is highly inaccurate as the time between the recordings corresponds to the sampling frequency. The pressure surge measured of 1.12 bar is consistent with a maximum of 1.25 bar predicted. It can be concluded that it is, indeed, possible to generate a liquid hammer that in the conditions of the test rig represents an overpressure of around 2%, which is low and does not cause concerns. It is worth noting that the test showed only one overpressure spike, that is unlike what is observed in water based systems in which a series of over and under pressure waves are observed. A plausible explanation is that the liquid CO_2 is closer to its saturation point, which tends to induce the formation of vapor and a very

fast damping. It can therefore be concluded that hydro-acoustic phenomena of liquid hammer type can occur in a CO_2 based district heating and cooling network. However the magnitude of the phenomenon should not be a source of major concern. For more test data and analyses, see [14].

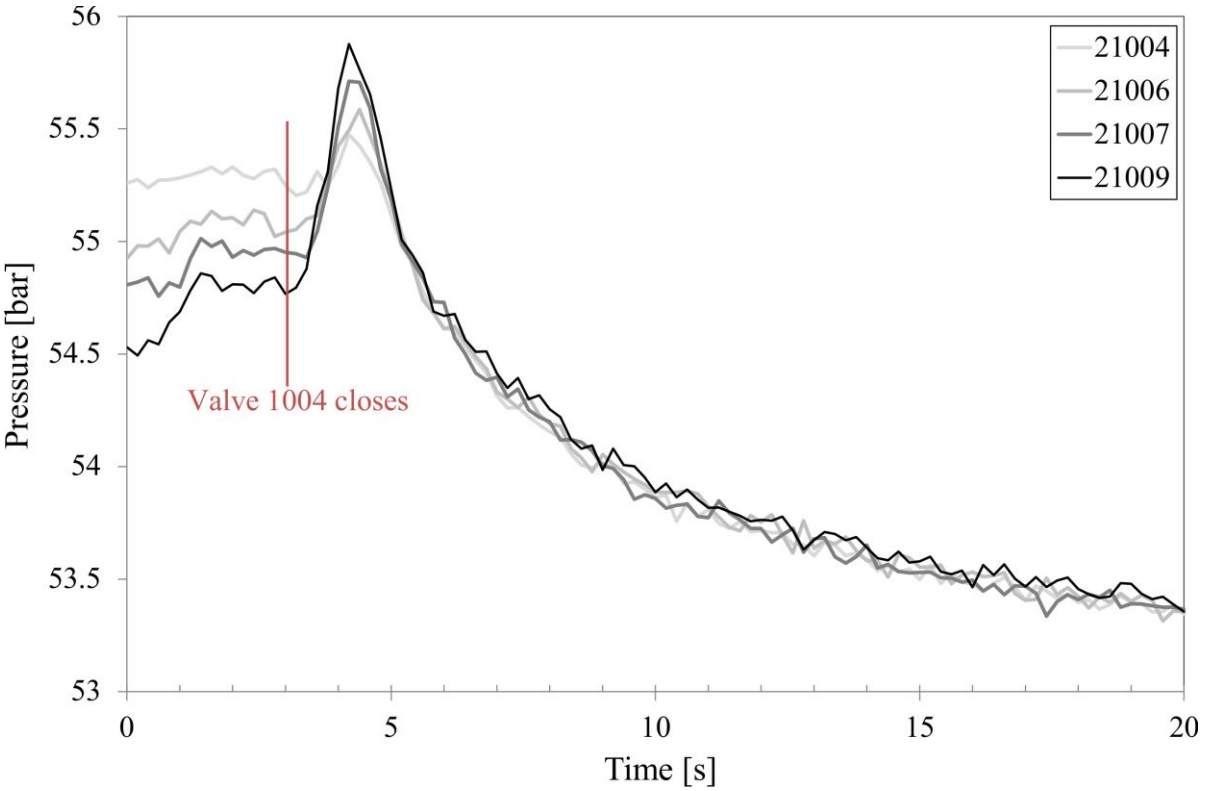


Fig. 9. Liquid hammer triggered by the closure of one of the network's sectioning valve when the system was operated at high load

4. Further extension of the concept

The proposed 2 pipe CO_2 energy network does not only allow for cold and warm energy supply via decentralized heat pumps when required, but it can also be a real umbilical cord in the city for further duties and improved synergies. Other uses include:

1) Supply of an extinguishing agent in case of fire, either directly in non-occupied rooms or indirectly using mixing ejectors to reduce the excessive concentration of CO_2. Such a mixing is rather easy when exploiting the large pressure difference between the CO_2 and the room pressure.
2) Supply of a cold source for Organic Rankine Cycles or other waste heat conversion or cogeneration devices.
3) Provide a collecting and transporting pipe for CO_2 to be collected from decentralized cogeneration units, such as fuel cells based systems. One example of adequate cogeneration unit is the hybrid SOFC fuel cell integrated with a inverted gas turbine cycle with CO_2 separation [15]. This concept takes

advantage of the SOFC inherent oxygen separation from air, since only oxygen is allowed to migrate through the solid electrolyte. For SOFC concepts, in which the anodic and the cathodic exhaust flows are kept separate, the anodic flow contains mainly CO_2 and H_2O. The latter can therefore be condensed locally and pumped, to be released at atmospheric pressure while the CO_2 is compressed to be injected in the CO_2 vapor pipe of the CO_2 DHC network. The CO_2 collected could be, either shipped to a long term underground storage site or, better, used at the central plant to generate synthetic methane when solar H_2 is available. Such a scheme would allow a synergy between the natural gas and the DHC networks and provide a storage for excess renewables in modern cities.

4) Be combined with daily electricity storage scheme using, at the central plant, alternatively a trans-critical CO_2 heat pump storing heat in a hot water reservoir when excess electricity is available, and its reversed counterpart CO_2 power cycle to generate electricity when needed [16]. Here also the DHC CO_2 network could be exploited as a cold or hot source for the ORC or heat pump cycles.
5) Serve as cold source for a gas driven heat pump that can be either of absorption type or based on integrated ORC and reversed Rankine cycle as proposed in [17].

5. Conclusion

District heating and cooling networks based on the use of the latent heat of a natural fluid like CO_2 represent an interesting option to develop high efficiency city district by providing a very compact energy network allowing to favor the synergy between the needs of the various users. Towards a city without cooling towers and chimneys is the vision that is analyzed in this paper with one 2 pipe network and decentralized heat pumps in each building. A final energy consumption reduced by more than 80% has been calculated on a real city district compared to existing technologies for heating and cooling. In spite of the relatively high pressures required by a CO_2 DHC network, experiments, at reduced scale, so far have not shown any major pressure surge concerns. Studies are in progress to convince developers to apply it on a large scale in a city.

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