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DIRECT CO_2 GROUND CONDENSERS

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ABSTRACT

The utilization of a direct condensing CO_2 ground heat exchanger as an auxiliary heat rejection device for commercial or industrial refrigeration applications offers several advantages. During the cold season, and especially when periods with frost and snow occur, the heat can be utilized to keep roadways safe. During the summer, the ground temperature is lower than the ambient temperature during the hottest hours of a day, i.e. the heat rejection can be performed successively: first towards the ambient air and thereafter towards the ground.

Many retail stores and distribution halls find it necessary to install snow melting devices in the ground below the area where trucks are loaded. They also install large condensers on the roof for rejecting surplus heat from the refrigeration system. To reduce installation costs and enhance energy efficiency, the two needs should be combined, and the heating performed directly via ground heat exchangers instead of implementing indirect systems as is often the case today.

However, it is important to ensure safety and sufficient heat transfer for the concept to be applicable. It is found that this requires i.a. seamless pipes without welding joints in the ground, segmentation of the heat transfer area, service trenches and smart control.

Keywords: CO_2 ground condenser, CO_2 commercial refrigeration, distribution centres

INTRODUCTION

During a case study for a distribution centre in Norway, the need for active snow melting was addressed. This is a normal demand for outside areas of shops, distribution centres, etc. in cold climate areas. Normally, this is done by direct electric heating, however, it would be more energy efficient if surplus heat from the refrigeration system could be utilised by condensing the refrigerant close to the surface. To cover the need for snow melting, it was suggested to use the parking place as a direct, giant condenser for the working fluid CO_2, which will be applied as the main refrigerant for the entire distribution centre. This is an innovative idea that could enable significant energy savings for the end-users. This concept can also be applied as auxiliary heat rejection device during hot summer days and reduce investment costs (less roof top heat exchangers). However, no such system exists today.

There are similar systems like:

- Ice in skating halls is prepared with such pipes with CO_2 evaporating directly, thus one can apply similar concepts for ground condenser systems. (Rogstam 2016)
- Direct expansion ground evaporators for heat pumps. (Eslami-Nejad et al. 2014)
- The concept of snow melting in itself is well-known and widely used, however, either directly with electricity or a secondary fluid with is pump circulated.

Steel pipes with a design pressure of up to 300 bar are available on the market. However, to the best knowledge of the authors, no direct heat rejection system exists so far.

Thus, from a technical point of view this should be possible, however, how should such a system be designed, installed, and maintained? This paper presents the work in performing a design approach for such a system, its pros and cons, important challenges/issues that must be addressed and other important findings related to the possible installation of such a direct ground heat exchanger for transcritical CO_2 applications.

CHALLENGES

In the first place, an identification of the requirements to the ground condenser are necessary. Snow melting typically requires a specific heat flux of 250 Wm^{-2}, and must heat, i.e. remove ice from a defined area around the building. For a typical distribution centre, the required zone for snow melting was 25 metres away from the building along the entire length of the building (250 m). To make the results of this work easily transferable to other cases, the CO_2 heat rejection device has been designed with several tubes in parallel. The tube length of each segment is 4x25m (each tube at 100 m), as shown in Figure 1. The integration point of the supply and return manifolds for the ground condenser to the centralised refrigeration plant of the entire distribution terminal is downstream of the main air-cooled heat rejection devices. These rooftop heat exchangers can be bypassed during winter operation, when all heat is required to heat up the yard. In case of high summer ambient air temperatures, the ground condenser further reduces the CO_2 temperature downstream of the gascoolers.

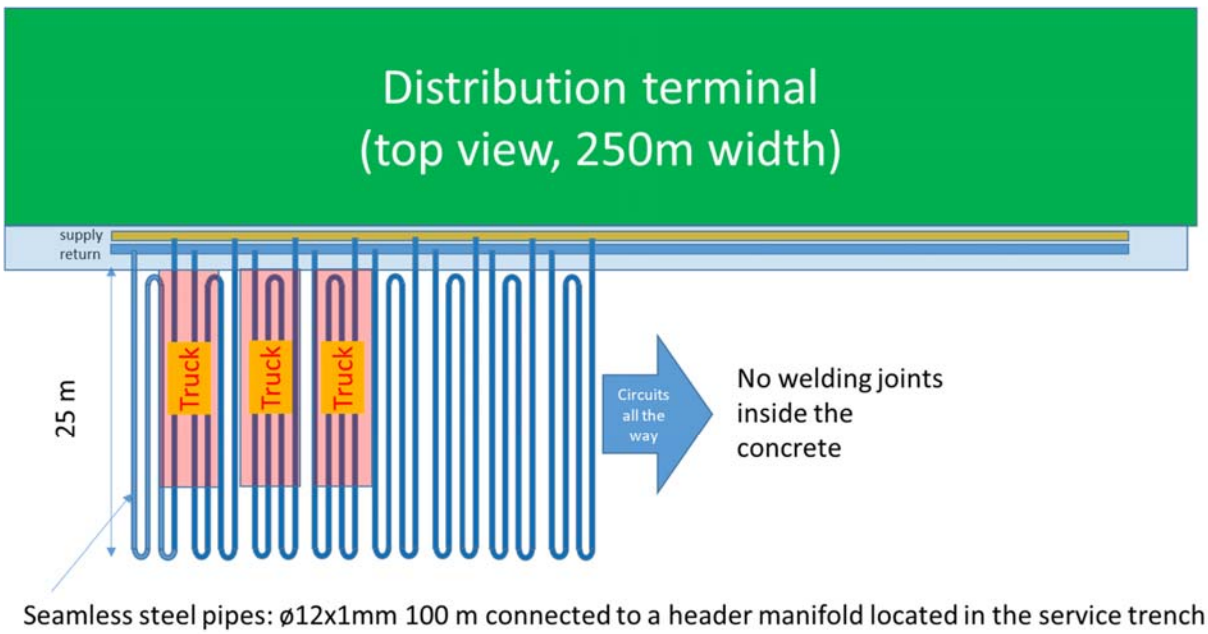

Figure 1: sketch of distribution building and CO2 ground condenser arrangement

The CO_2 pipes inside the concrete will be the most expensive part, and should be of some normal standard size, and enabling sufficient heat transfer. They have to withstand the high pressure inside the pipes (during summer time heat rejection), but also handle that trailers park on top of the concrete in which they are buried. Other challenges involve how the pipes can be built and maintained in a practical way, strategies in cases of leakage and prevention of implosion of system pressure due to low ambient temperature conditions. Hence, the heat rejection device must handle the following challenges:

1. Sufficient heat transfer
2. Safety – high pressures in the pipes
3. Avoid leakage, stopping the refrigeration system
4. Implosion too low return temperature
5. Service, construction, maintenance

Each of these will be addressed more closely in the following sections.

SOLUTIONS

1. Heat transfer

In order to justify the investment and to reduce the number of air cooled heat exchangers, a sufficient heat transfer performance of the ground condenser is required, both during the winter time and during the summer period. Typical inlet and outlet conditions of the CO_2 from the refrigeration unit are described, suitable geometries sets and pipe dimensions determined from these and a target velocity of maximum 1 m/s. If the heat transfer is then insufficient, the geometric sizes will be changed within reasonable ranges. The entire cross sections of all pipes was set to achieve an inlet velocity of around 1 m/s. Reasonable geometric values were assumed to be as in Table 1.

Table 1: Geometrical values for initial design of the ground condenser

Parameter	Value	Unit
Length	25	m
Width	100	m
Distance between pipe centres	0.15	m
Inner pipe diameter	0.006	m
Wall thickness	0.001	m
Depth (surface - pipes)	10	cm
Based on this:		
Cross sectional area	2.83E-05	m^2
Inner surface area per pipe	0.47	m^2
Number of pipes	666	-
Required heat	625	kW

During winter mode, the high side pressure of the CO_2 refrigeration system will be low, typically 50 bar. The suction pressure is around 30 bar for compressing typically from a cold room at temperatures around 2-4°C to 50 bars with 70% isentropic efficiency results in a discharge temperature of 40°C and around 14 °C condensing temperature. The CO_2 will be subcooled and leaves the heat exchanger at 5°C (the ground will be above 0 °C upon snow melting), one obtains the data in Table 2.

Table 2: Assumed, typical CO_2 state and properties at inlet and outlet in winter mode.

	In	Out	Unit
pressure	50	50	bar
temperature	26.4	5	°C
enthalpy	446	211	kJ/kg
viscosity	1.67E-05	1.39E-05	kg/ms
density	129	906	kg/m3
thermal conductivity	2.32E-02	0.106536	W/mK
Prandtl no.	1.30976	2.28024	-

From this, one can obtain the Reynolds number and Nusselt number at inlet and outlet. An estimation of the UA-value, assuming that:

1. A layer of pipes with small distances between, evenly distributed in the ground, can be seen as a plate at the same depth, and
2. That the heat transfer coefficient is constant at in- or outlet, is also given. It is clear that the UA-value hardly changes from inlet to outlet, and the resistance in the ground is the determining factor. Considering the values along the entire pipe, at all vapour qualities, the development in UA-value is shown in Figure 2.

Table 3: Reynolds and heat transfer numbers for the CO_2 ground condenser at inlet and outlet, with estimated UA-value provided the heat transfer coefficient at inlet or outlet is constant and valid for the entire length, and estimated overall heat transfer based on the average of the two

	Inlet	Outlet	Unit
Re	50751	60826	-
Nu	145	198	-
α	561	3514	$Wm^{-2}K^{-1}$
UA	13.89	13.97	WK^{-1}
Q	448		kW

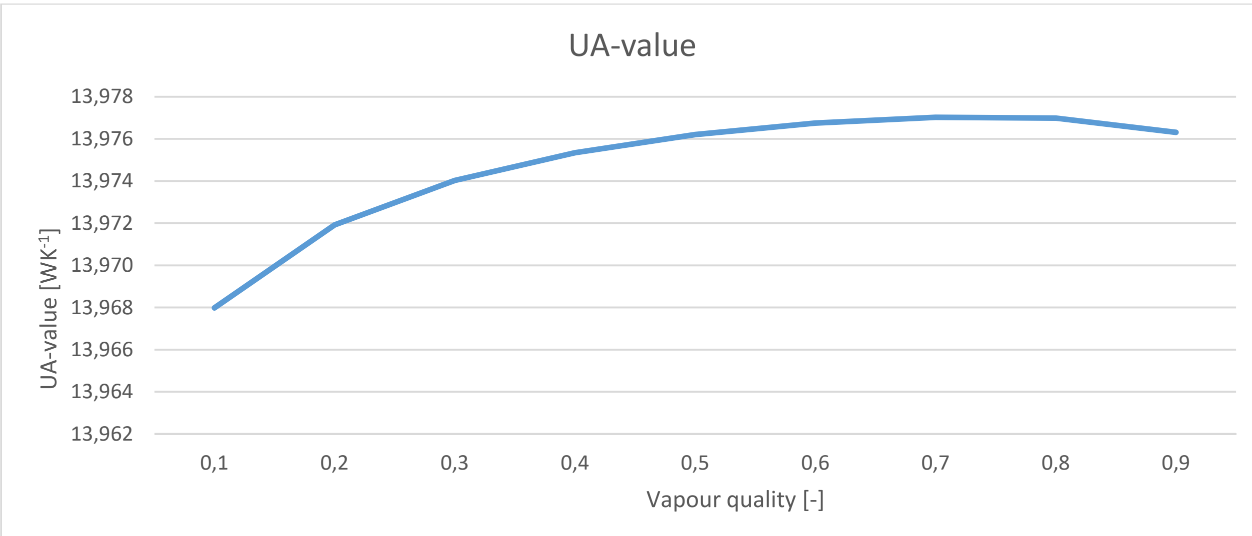

Figure 2: Calculated UA-value for different vapour qualities during condensation shows hardly any change along the pipe length

However, when evaluating the initial simulation results of the total heat Q, also shown in Table 3, it turns out that the condensation will not be completed, and the heat transfer surfaces are insufficient. Hence, as the heat transfer resistance in the ground is dominating, one must either reduce the depth or the pipes must be made longer to ensure complete condensation and sub-cooling. Reducing the depth (between tubes and surface) to around 7 cm increases the heat transfer to the desired value. Sufficient strength (total concrete thickness and ground support) of the entire ground elements is needed, since this part is trafficked by heavy goods vehicles.

For verification of the first assumption, that many pipes close to each other in the ground have nearly identical heat transfer as a surface at the same depth, the simulation programme COMSOL Multiphysics 5.1 was applied (COMSOL 2018). This is a simulation programme allowing simulation of both fluid flow, electric flows, magnetism, mass transfer, heat transfer and more in various materials and self-designed geometries. Both 1, 2 and 3D simulations can be performed, transient or stationary.

For this situation, a stationary 2D model of two segments of concrete were made, one with twenty copper pipes beside each other and one with a copper plate. These were assumed to be at the condensation temperature for CO_2 at 50 bar, 14.3 °C. The surface temperature was set to 0 °C, constant, and the sides of the segments were thermally insulated. The segments were made 20 metres deep, as the ground temperature below 15 metres is quite stable, and 20 metres should thus be more than sufficient to set a constant temperature. This varies with location, but 9 °C is a representative value (Sanner 2009). The surface heat flux was integrated at the top of bot segments and compared.

Simulation in COMSOL showed that the heat flux became about 32% larger than the correct value when assuming a plate instead of individual pipes. As the plate had the desired value, the depth of the pipes was decreased until it reached the same value of heat flux, ending at a depth of 54 mm. This is still within the normal range of depths (Liu and Spitler 2004), and should hence be applicable.

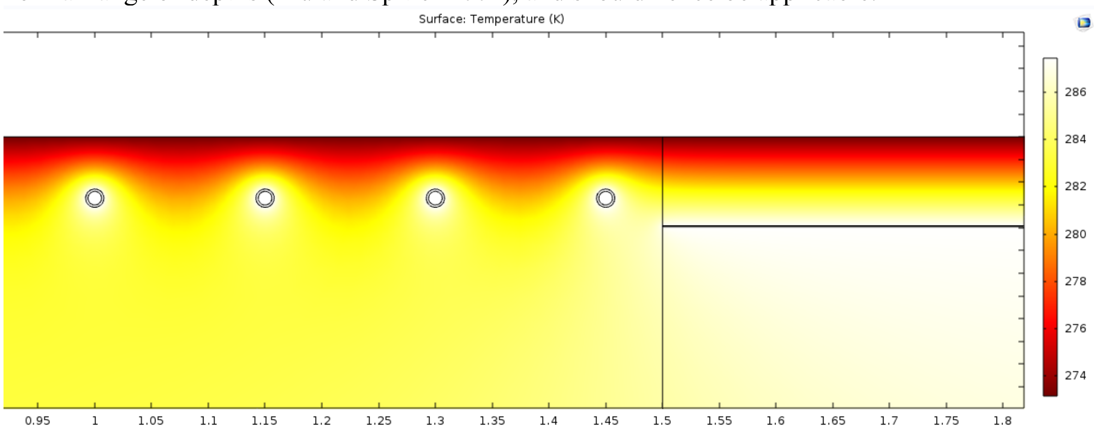

Figure 3: Display of the spatial temperature distribution in the ground around four of the twenty pipes in the ground and the plate which was assumed to be equivalent to them: the pipes are here elevated to achieve the same heat flux as the plate.

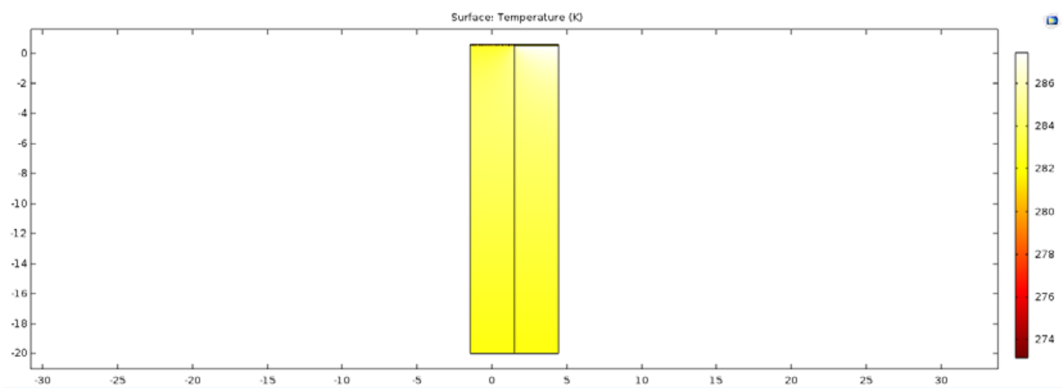

Figure 4: The spatial temperature distribution in the entire concrete segments modelled in COMSOL with twenty pipes (left) or a simple plate (right) to compare their heat transfer to the surface. The difference downwards diminished after around 4 metres.

2. Piping

Utilization of safe, strong pipes, available in the market: There is a chance of using existing pipes for cooling skating halls, where the concept is in use on the evaporation side. However, the pipes must withstand higher pressures for condensation/gas cooling than for evaporation, hence, seamless steel pipes delivered on coil are recommended.

3. Segmentation

All pipes will be placed in each their separate concrete segment. Ends that must be welded will only be outside inside the service trench. The condenser will be made of several segments connected to keep the truck parking space free of ice. This segmentation allows closing and removal of one segment upon leakage, rather than shutdown of the entire system.

Parking places are often made with small ditches for drainage of rainwater, and building the system with such small channels between the segments will make installation, replacement and service maintenance easier. To ensure good flow through the pipes, minimal heat transfer from one hot pipe to another and pure liquid at the outlet.

4. Implosion

If the CO_2 is cooled below ca 5 °C in the heat rejection devices, then it will end up as pure, subcooled liquid upon throttling. If subcooled liquid enters the separator, vapour inside the separator would condense very fast and cause an implosion, i.e. the pressure level inside the separator of the CO_2 booster system cannot be maintained. As the outlet temperature of the CO_2 from the condenser cannot be securely controlled, one option is to enable heat exchange between return line and discharge gas/bypass of discharge gas to prevent implosion, or hot gas injection to the separator. However, the number of active ground condensers should be adapted to the available heat, to prevent an uncontrollable situation with respect to the high side pressure.

5. Service trench

For simple service, construction and maintenance, a trench should be made by the building, between the wall and the parking place for all pipe ends and welding, see Figure 1. Thus, service connections are placed only at the ends and easily/readily accessible for maintenance and service.

Such a trench in front of the building also allows a few other advantages related to future needs for effective, automatic fuelling of trucks (hydrogen or battery). It could be a path for robots transporting batteries to and from trucks being loaded or attaching hydrogen supply. Hydrogen, batteries or some other energy carrier for transport systems will be standard in the near future.

DISCUSSON

An alternative way to perform heat exchange with the ground would be to have a large secondary loop below the yard. This technology is state of the art for ground source heat pumps; a biodegradable secondary fluid like an ethanol water mixture should be applied prior glycol fluids with a significant environmental impact when leaking into the ground. However, such a secondary loop arrangement would not be as efficient in operation but might be possible to implement due to lower first costs, with lower operation pressures inside plastic pipes.

Such a ground heat exchanger could theoretically also be implemented with current non-natural working fluid systems. However, the additional refrigerant charge, and the corresponding additional cost makes such an application less feasible. Due to the remarkable thermodynamic and fluid properties of CO_2 as a refrigerant, the losses due to long distances pipes and heat transfer are much lower compared to a conventional low-pressure working fluid. Even if a secondary loop circuit is applied, as described above, still the total energy efficiency of applying CO_2 in the main refrigeration system would outperform a conventional non-natural working fluid system. If the main refrigeration system is an ammonia-based unit, a secondary loop circuit with oil-free CO_2 should be considered.

SUMMARY

A new concept for a ground condenser for CO_2 refrigeration systems has been described and designed. It offers several advantages of snow melting, reduced investment costs in roof condensers, lower return temperature and higher energy efficiency.
Several challenges have been identified and solutions are described. The system should be made as segments for easy construction, cut-off upon leakage, repair and demolition, and a service trench should be foreseen between these and the building for access, service and maintenance. The trench can also offer other advantages related to service and fuelling of trailers.
Existing seamless pipe technology delivered on coils can be used, and proper design regarding length, depth and sizing is crucial to ensure sufficient heat transfer. The results demonstrate that the system can be implemented and should operate satisfactorily all year.

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