POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Energy targeting for heat recovery from carbon capture processes using hybrid absorption heat pumps

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

AUTHOR: GIANLUCA ABRAMI

ADVISORS: TOMMASO TOPPI, SIMON HARVEY

CO-ADVISOR: MAX BIERMANN

ACADEMIC YEAR: 2020-2021

1. Introduction

District heating (DH) represents one possible solution for the decarbonization of the heating sector, a fundamental step to reach the 1.5 °C limit imposed by the Paris Agreement.

Waste-to-Energy (WtE) plants are an important source to district heating networks, especially in the Scandinavian countries, where heating demand is present throughout most of the year. This technology, however, is far from being carbon free, since fossil CO_2 emissions are associated to the flue gases released in the atmosphere.

For this reason, carbon capture and storage technologies (CCS) are being investigated as a possible solution to reduce the CO_2 content of the flue gases. The downside of such a configuration is that the CO_2 capture is an energy intensive process, requiring a considerable amount of heat. In the most straightforward layout, this heat demand is satisfied by low pressure steam bled from the WtE plant turbine, thus determining a loss in the original district heating supply.

At the same time, residual heat could be recovered from the CCS plant in order to compensate for the district heating supply loss.

In this context, heat pumps could further increase the amount of heat recovery, exploiting lower temperature residual heat. Since waste heat recovery and district heating supply are normally characterized by large temperature glides, the hybrid absorption compression heat pump (HACHP) represents a paramount candidate for such application, due to the non-constant evaporation and condensation processes, that allows to decrease the temperature difference with the source/sink during the heat transfer process [1], with a positive impact on the efficiency.

To properly integrate heat pumps in such complex heat recovery processes, pinch analysis is often exploited. This methodology, in fact, provides a consistent and straightforward approach in the heat exchanging network design and therefore plays a significant role in the development of an efficient heat recovery system [2]

1.1. Aim & Scope

This thesis evaluated waste heat recovery solutions from a possible future carbon capture unit implemented in boiler number 7 of the Sävenäs Waste-to-Energy plant, located in Gothenburg (Sweden). Process integration methods and tools were used to establish targets for maximum heat recovery, combining together direct heat recovery and a hybrid absorption-compression heat pump, aiming at minimizing the loss of energy of the district heating network. The hybrid heat pump was then compared to a single stage vapor compression heat pump (VCHP) both from technical and economic point of view.

2. Hybrid absorption heat pumps for waste heat recovery

A schematic representation for the hybrid absorption compression heat pump working with the zeotropic mixture ammonia-water is proposed in Figure 2-1.

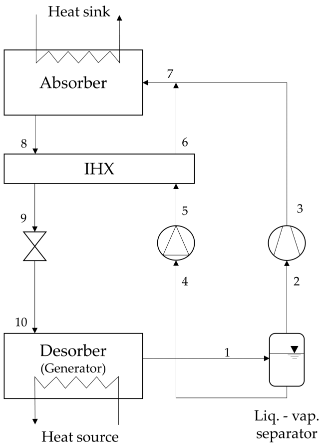

Figure 2-1: Schematic representation of a HACHP

Compared to a conventional vapor compression heat pump, evaporator and condenser are replaced with a desorber (often named generator) and an absorber respectively. With reference to Figure 2-1, in the generator the so called "rich solution" of ammonia-water enters at low pressure (point 10); here ammonia vapor is desorbed from the liquid solution of ammonia-water by heat provided from the low temperature external source.

A phase separator divides the liquid solution (named "poor" solution, point 4) from the refrigerant vapor (point 2); the former is pumped to the high pressure level of the cycle, while the latter is compressed.

At high pressure level the liquid and vapor streams are reunited to perform the absorption process: the ammonia vapor is absorbed into the poor solution, releasing heat to an external sink. The "rich solution" leaving the absorber (point 8) flows through an internal heat exchanger and an expansion valve, before the cycle restarts.

The main advantage of this technology, compared to a vapor compression heat pump is related to the non-isothermal processes occurring in the low- and high-pressure heat exchangers, allowing to decrease the temperature difference with the external source/sink and thus the entropy generation due to heat transfer process [3]. Figure 2-2 clarifies this concept in the temperature-heat diagram, where absorption and desorption processes are compared with condensation and evaporation respectively.

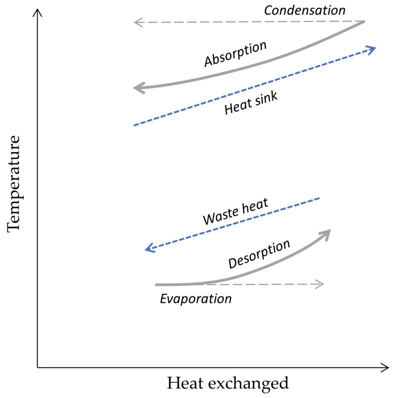

Figure 2-2: Heat-temperature profile of desorption and absorption processes compared to evaporation and condensation

Since, normally, waste heat sources and district heat sinks are characterized by large glides, this technology is of particular interest for such applications, guaranteeing high efficiencies.

3. Method

The analysis performed in this project follows three steps:

1. Definition of the reference case and calculation of the original district heating supply (as it is nowadays).
2. Carbon capture and conditioning processes integration in the reference system and numerical simulation. The heating/cooling duties of the CCS plant,

the direct heat recovery possibilities and the impact on the DH network are evaluated.

3. Heat pump integration: pinch analysis and numerical tools were exploited to correctly integrate in the system a HACHP. This device was then compared to a VCHP, in the same boundary conditions, in terms of efficiency and capability to recover waste heat from the CCS plant to feed the DH network.

3.1. The reference case

A scheme of the reference system, prior CCS integration, is presented in Figure 3-1.

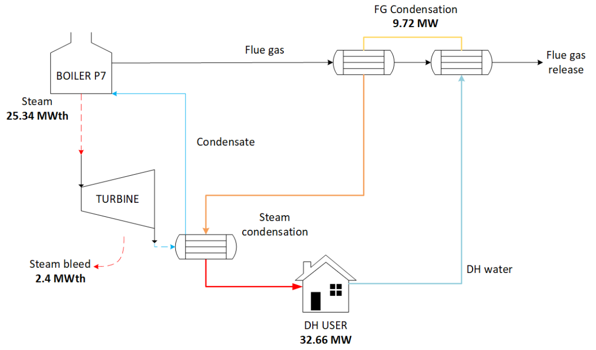

Figure 3-1: The reference case (prior CCS integration) with total district heating supply.

Boiler P7 generates high pressure steam, which is fed to a turbine, linked to a generator for electricity production; the heat of condensation released by the steam is recovered to district heating water, which is also preheated by the flue gases treatment process.
The total heat capacity from boiler P7 to the DH network was calculated to be 32.66 MW.

3.2. CCS modelling

CO_2 capture and conditioning models were built in ASPEN PLUS V12 in previous works. However, they have been modified to match the amount of CO_2 present in the flue gases of boiler P7; the CO_2 capture rate was set to 90 %. The assumed location of the CO_2 capture plant is downstream of the flue gas condensation unit and the solvent is a 30% acqueos monoethanolamine, a widely used benchmark.
A simplified representation of capture and conditioning models is proposed in Figure 3-2.

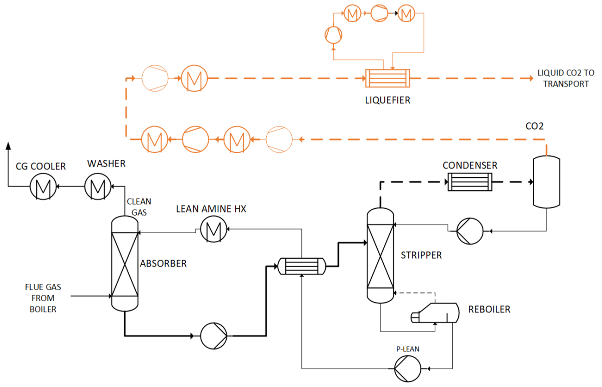

Figure 3-2: Capture (black) and condition (orange) section built in ASPEN PLUS V12, simplified representation

Detailed description for the capture model can be found in [4], while the conditioning section was based on the work of Deng et. Al [5].
The main purpose of such models was to obtain consistent data regarding heating and cooling duty of the capture and conditioning processes.
The simulation revealed a reboiler heating needs of 12.3 MW. In case this is supplied by low pressure steam bled from the turbine, a loss of 37.7 % of the heat available for the DH network is determined (compared to the reference case).
Concerning the cooling duty (which can be interpreted as residual heat availability) the conditioning section contribution was found to be negligible compared to that of the capture section (around 93% lower). For this reason, it was discarded from the analysis, not providing any real benefits to heat recovery solutions.
Eventually, discarding the washer of the capture section (because of negligible heat content), three coolers are identified as potential waste heat sources: the clean gas cooler, the CO_2 condenser and the lean amine cooler (these are represented in Figure 3-2 and they are named “hot streams” by pinch analysis theory). The total heat availability is equal to 13.85 MW, included in a temperature range of 101–20 °C, but mainly related to low temperature (below 60 °C), as one can notices by looking at the hot composite curve in Figure 3-3. Considering supply and return temperature of district heating (named “cold stream”) respectively equal to $T_{sup} = 103\,°C$; $T_{ret} = 41\,°C$ (averages DH network temperatures of winter/spring term at Sävenäs plant) and a minimum temperature difference between hot and cold streams equal to $\Delta T_{min} = 5°C$, pinch analysis methodology revealed that only 4.73 MW could be directly recovered to

district heating water, and additional hot utility of 568 kW is required to reach the targeted supply temperature (see Figure 3-3). For this reason, the integration of a heat pump is highly advised.

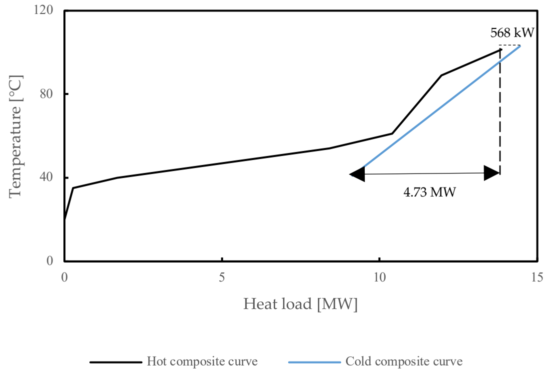

Figure 3-3: Hot and cold composite curve in the case of direct heat recovery only

3.3. Heat pump integration

The so called "background process" (BG process) identified by pinch analysis theory is composed of the hot streams of the capture section, completely defined in terms of temperature and heat duty, and one single cold stream, representative of district heating water; supply and return temperatures of this stream are defined and its capacity ($Q_{DH,rec}$) is equal to heat that can be recovered from the hot streams, considering both direct heat recovery (Q_{direct}) and heat pump (Q_{HP}), as stated in equation (3-1).

$$Q_{DH,rec} = Q_{direct} + Q_{HP} \tag{3-1}$$

The challenge of this approach is that Q_{HP} depends on the heat input to the heat pump and on its working conditions, and thus cannot be established "a priori". An iterative procedure was thus developed to match the grand composite curve (GCC) and heat pump models.

In particular, with reference to Figure 3-4 , the black curve provides the GCC for a given value of $Q_{DH,rec}$. This curve clearly divides the BG process in two regions: below and above the pinch point, where residual heat and heat deficit of the BG process are respectively represented. A heat pump properly integrated in such a system must recover residual heat below the pinch point, lift its temperature and discharge it above the pinch point. The heat pump should supply the entire hot utility demand (Q_{HU}), in order not to introduce additional external hot utility.

To properly interface the heat pump with the background process taking into account all the streams involved in the heat exchanging processes, heat recovery loops (HRL) are used, following the approach proposed by [6]. The minimum temperature difference between BG process-HRL and between HRL-heat pump were both set to 5 °C.

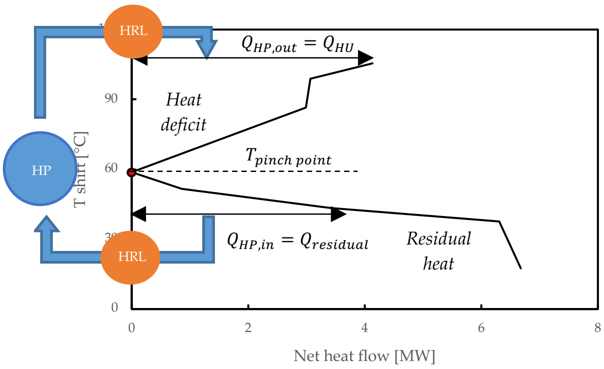

Figure 3-4: Heat pump integration in the GCC of the background process (for a given value of $Q_{DH,rec}$)

The iterative procedure that was implemented exploited both the GCC and a numerical model of the HACHP built in STACY, an innovative modeling tool for the steady state simulation of absorption cycles [7]. The purpose of such procedure was to guarantee a generator heat duty, as revealed by STACY simulation, equal to the considered residual heat below the pinch point, shown in Figure 3-4. At the same time, the absorber heat duty must be equal to the hot utility needs. Also, the COP of the heat pump was maximized by iteratively varying the concentration of the rich solution of ammonia-water.

Four different scenarios were analyzed, depending on the choice of generator cutoff temperature: the lower is the cutoff temperature, the more residual heat can be exploited by heat pump's generator; consequently, more heat can be delivered to the background process by the absorber, increasing the capacity of the recovered district heating stream (see equation 3-1). In practice, four shifted temperature levels of residual heat of the background process were selected: 43.5 °C, 39.7 °C, 37.5 °C and 32.5 °C; these will be used to identify the different scenarios.

In each of the analyzed scenario, the hybrid heat pump was compared to a standard vapor compression heat pump (VCHP). The comparison was carried out for the same amount of $Q_{DH,rec}$, which was found through the matching procedure of the HACHP, illustrated just above.

Given that the VCHP cannot be simulated in STACY due to some fluid missing data, a thermodynamic model for a single stage vapor compression heat pump was developed in MATLAB: this allows to characterize the thermodynamic stages of the heat pump´s cycle in term of pressure, temperature, enthalpy and entropy.

An iterative procedure (similar to that of the HACHP) exploiting both the numerical model and the GCC was exploited to find the evaporator temperature and heat duty compatible with condenser working point, as defined by the hot utility needs of the background process.

The main hypothesis for both heat pump models are reported in the next paragraph, while a detailed description of the iterative procedure is present in complete thesis report.

The comparison between the HACHP and VCHP mainly focused on technical parameters, such as heat input, COP, electrical power consumption and the working point of the compressor, characterized in term of discharge pressure and temperature, pressure ratio and volumetric heat capacity.

Also, assuming that the HACHP has a higher investment cost (due to higher number and more critical components), but lower operational expenses (due to the savings in electrical power consumption) a simple economic analysis was performed; the two technologies in fact, have been compared in terms of ΔTIC (differential total investment cost), i.e. the maximum additional investment cost which can be accepted for the HACHP compared with the VCHP.

Hypothesis for the economic analysis:

- $Lifetime\ =\ 20\ years$
- interest rate = 10 %, $inflation = 2\%$
- $price_{el} = 40\ \div 130\ {€}/_{MWh}$
- $Op.\ hours = 7920\ {h}/_{year}$

3.3.1 Heat pump models

Concerning the STACY model of the HACHP, generator and absorber were modeled as counter current liquid/solution heat exchangers. The minimum temperature difference with the external loops was set to $\Delta T_{min} = 5°C$. Pressure drop of 20 kPa was considered in the absorber, while it was neglected for the generator. Isentropic efficiency of compressor and pump was set to 0.7, while efficiency of electric motors to 0.9.

Regarding the MATLAB model of the VCHP, the compressor isentropic efficiency was set to 0.7, superheating and subcooling degree respectively equal to 10 K and 5 K. Pressure drops on both heat exchangers were neglected.

The chosen refrigerant for the VHCP model was R600, since this is characterized by decent COP values and high volumetric heat capacity $(\frac{heat\ output}{volume\ of\ processed\ refrigerant}[\frac{J}{m^3}])$ in the temperature range of this application. Also, R600 is often indicated as one of the most promising alternative for high temperature heat pumps in the immediate future [8].

4. Results

HACHP refrigerant profile (red curve) is represented against the background process (black curve) in Figure 4-1; the dashed blue curve is representative of the refrigerant profile of the VCHP. As one can notice looking at Figure 4-1, the average temperature differences with the background process are much lower for the HACHP.

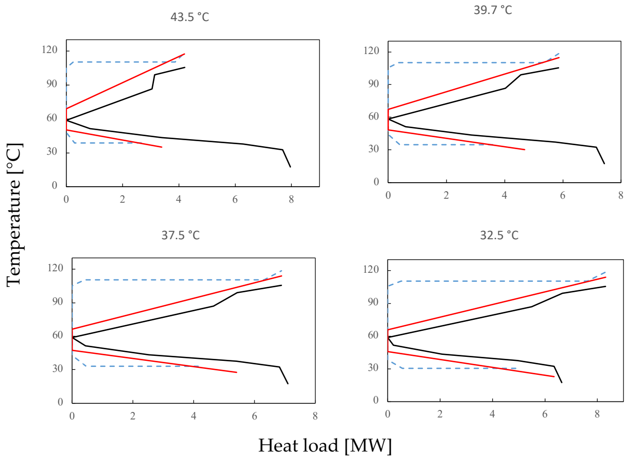

Figure 4-1: HACHP and VCHP represented against the background process in the different scenarios

The lower is the cutoff temperature in the generator (evaporator), the more heat is processed by the heat pump and thus more heat is delivered

to the district heating water; it must be highlighted that, in the lower shifted temperature scenario, not only the heat delivered by the heat pump is increasing, but also the direct heat recovery.
The total heat recovered to the district heating network in the different scenarios is summarized in Table 1, together with heat delivered by the heat pump (note: the difference between $Q_{DH,rec}$ and $Q_{HP,out}$ corresponds to direct heat recovery capacity, according to equation (3-1))

Table 1: Total DH delivery in the different scenarios, together with heat pump delivered heat

Scenario	$Q_{DH,rec}$ [MW]	$Q_{HP,out}$ [MW]
43.5 °C	10.1	4.2
39.7 °C	12.3	5.87
37.5 °C	13.65	6.89
32.5 °C	15.54	8.32

The scenario at 39.7 °C is the one that perfectly compensates for the district heat supply loss associated to reboiler heat demand (equal to 12.3 MW) and is therefore identified as the "base case".
Eventually, the 32.5 °C scenario is the one in which the HACHP is exploiting the maximum amount of residual heat, with a total district heat recovery of 15.54 MW. This implies that, not only is possible to completely compensate for the district heat supply loss associated to CCS integration, but also to increase the total amount of heat delivered to district heating water by 9.9 % compared to the reference case.
The more heat is recovered by the heat pump, the lower is the COP, due to lower temperature of residual heat exploited. Figure 4-2 compares the COP of the two heat pumps in the different scenarios: the COP of the HACHP was found to be almost the double of the VCHP.

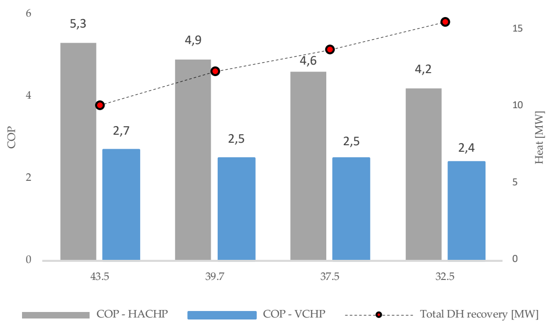

Figure 4-2: COP of HACHP and VCHP in the different scenarios

Because the COP of the VHCP is lower than the one of the HACHP, for the same amount of heat delivery, the VCHP consumes more electricity than the HACHP; for this reason, the evaporator duty is lower than the generator one (Figure 3-4 clearly shows that, below the pinch point, the dashed blue line is shorter than red line). This determines a higher cooling demand of the BG process in case a VCHP is exploited.

Concerning the working point of the compressor, the VHC and pressure ratio were found to be favorable for the hybrid solution: the former, in fact, was found to be around six times higher for the HACHP, varying from 15 to 10.2 $\frac{MJ}{m^3}$ (from higher to lower shifted temperature scenario); the same parameter for the VCHP ranged from 2.3 to 1.8 $\frac{MJ}{m^3}$. The pressure ratio of the HACHP was included in a range of 2.8 to 3.8, being around the half of that of the VCHP (5.4 to 6.8).
Consistently with ammonia thermodynamic properties, discharge temperature and pressure of the HACHP compressor were found to be much higher than the one exhibited by R600.
The ammonia discharge temperature, in fact, was included between 170 to 200 °C in the different scenarios, with a discharge pressure of 33 to 28 bar. R600 discharge temperature, instead, ranged from 120 to 122 °C, while its discharge pressure was equal to 19.5 bar (constant in the different scenarios due to constant condensation temperature).

Regarding the economics, Figure 4-3 shows that in the "base case" scenario, even considering the lowest electricity price and lifetime, a *ΔTIC* of around 0.62 M€ is found.

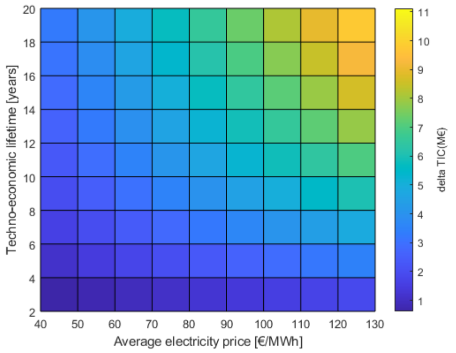

Figure 4-3: Delta TIC as a function of techno economic lifetime and average electricity price.

Since the lifetime of heat pumps and the average electricity price are likely to be higher than the

values considered just above and the difference in investment cost is likely to be lower than 0.62 million €, the HACHP is considered an attractive investment compared to the VCHP; its additional investment cost, in fact, can be relatively rapidly recovered due to the savings in operational expenses.
Similar conclusions can be drawn performing the economic analysis in the other scenarios.

5. Conclusions

This thesis project investigated residual heat recovery possibilities from a carbon capture and storage plant integrated in a Waste-to-Energy plant, developing a methodology to properly integrate hybrid absorption heat pumps in a such complex industrial process, exploiting both pinch analysis and heat pumps numerical modeling software.
The main conclusions can be summarized in the following three points:

1. Direct heat recovery from a post combustion carbon capture plant is limited by temperature level of hot streams. For this reason, the integration of heat pump in this system is highly advised.
2. For this application, the HACHP performs better than the VCHP, both from technical and economic point of view.
3. Pinch analysis revealed its relevance in heat recovery evaluation involving multiple sources (direct heat recovery and heat pumps).

6. Bibliography

[1] J. K. Jensen, W. B. Markussen, L. Reinholdt, e B. Elmegaard, «On the development of high temperature ammonia–water hybrid absorption–compression heat pumps», *Int. J. Refrig.*, vol. 58, pagg. 79–89, ott. 2015, doi: 10.1016/j.ijrefrig.2015.06.006.

[2] I. C. Kemp, *Pinch Analysis and Process Integration*, Second Edition. Elsevier, 2007.

[3] M. Ahrens, A. Hafner, e T. Eikevik, «Development of Ammonia-Water Hybrid Absorption-Compression Heat Pumps», ago. 2019, doi: 10.18462/iir.icr.2019.1869.

[4] S. Ó. Garđarsdóttir, F. Normann, K. Andersson, e F. Johnsson, «Postcombustion CO2 Capture Using Monoethanolamine and Ammonia Solvents: The Influence of CO2 Concentration on Technical Performance», *Ind. Eng. Chem. Res.*, vol. 54, n. 2, pagg. 681–690, gen. 2015, doi: 10.1021/ie503852m.

[5] H. Deng, S. Roussanaly, e G. Skaugen, «Techno-economic analyses of CO2 liquefaction: Impact of product pressure and impurities», *Int. J. Refrig.*, vol. 103, pagg. 301–315, lug. 2019, doi: 10.1016/j.ijrefrig.2019.04.011.

[6] Florian Schlosser, C. Arpagaus, e T. Walmsley, «Heat Pump Integration by Pinch Analysis for Industrial Applications: A Review», 2019, [Online]:https://www.aidic.it/cet/19/76/002.pdf

[7] M. Aprile, T. Toppi, S. Garone, e M. Motta, «STACY–A mathematical modelling framework for steady-state simulation of absorption cycles», *Int. J. Refrig.*, vol. 88, pagg. 129–140, apr. 2018, doi: 10.1016/j.ijrefrig.2017.12.019.

[8] O. Bamigbetan, T. M. Eikevik, P. Nekså, M. Bantle, e C. Schlemminger, «Theoretical analysis of suitable fluids for high temperature heat pumps up to 125°C heat delivery», *Int. J. Refrig.*, vol. 92, pagg. 185–195, ago. 2018, doi: 10.1016/j.ijrefrig.2018.05.017.