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LONG-DISTANCE TRANSPORT OF THERMAL ENERGY USING SORPTION CYCLES

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Summary

Networks of thermal energy transportation are classically based on sensible heat transport and thus they are limited to short distances. In order to realize a long-distance transport, thermochemical processes are investigated, and particularly an innovating system that couples two thermochemical dipoles. The advantages of this new system, the energetic performances and the operating cost of transport are presented. A comparison with chilled water network is also done.

Nomenclature

COP	coefficient of performance	λ	coefficient of pressure loss
c_p	calorific capacity, $J.kg^{-1}.K^{-1}$	λ_{th}	thermal conductivity, $W.m^{-1}.K^{-1}$
d	diameter, m	ρ	density $kg.m^{-3}$
e	thickness, m		
Δh	enthalpy, $J.kg^{-1}$	<i>Indices</i>	
L	distance, m	<i>comp</i>	compression
P	power, W	<i>C</i>	cold
ΔP	pressure loss, Pa	<i>G</i>	gas
T	temperature, K	<i>pump</i>	pump
u	velocity, $m.s^{-1}$	<i>S</i>	source
		<i>therm</i>	thermal
		<i>vap</i>	vaporization
<i>Greek symbols</i>			
η	efficiency		

1. Introduction

On account of the decentralised production of energy, major interests are expressed for long-distance transport of thermal energy. Energy is generally produced far from the user's location. Moreover thanks to such transport networks, industrial thermal wastes from thermal power stations and incinerators can be upgraded to become useful energy. Up to now, the transport of heat and cold are realised for short-distance applications by using sensible heat (hot or chilled water) or latent heat (vapour, ice slurry). Due to thermal losses and expensive insulation, the transport distance does generally not exceed 10 km of urban networks. For longer distance, it does not make sense to transport energy in sensible or latent form.

Other systems based on thermochemical cycles using endo and exothermic processes can realize long distance transport of thermal energy. Our study deals with

thermochemical process using solid/gas reversible chemical reaction. Thus, the transport of energy is simply realised by the reactive gas at ambient temperature. The coupling of several thermochemical dipoles is the originality of this work. Ideally, this system presents better energetic performances than classical process. The energetic and operating costs of transport are evaluated hereafter, and also compared with chilled water technique.

2. Concept of long distance thermal energy transport

2.1 Basic cycle

Different kinds of physico-chemical endo/exothermic processes can realize a basic sorption cycle: liquid/gas sorption (absorption) and solid/gas sorption (adsorption, chemical reaction). In this study, thermochemical cycles using reversible chemical reactions are prioritized on account of their higher energetic density.

Figure 1 shows a simple effect cycle. At the heat source site, an endothermic process produces a reactive gas. For example, this gas can be generated either by evaporation or the decomposition reaction of a salt. The gas flows at ambient temperature to the user site through a pipeline. It allows there a heat production thanks to the reverse exothermic process (condensation or synthesis reaction). The return of gas on user's location enables to close the cycle and a further cold production can also be provided. As the gas is transported at ambient temperature from one site to the other, there are no thermal losses during the transport, contrary to the sensible or latent heat transport. Consequently pipelines do not need to be insulated, reducing thus the investment cost of transport.

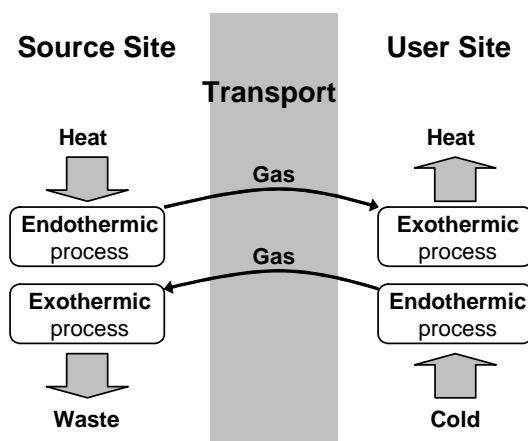


Figure 1: Representation of the concept for thermal energy transport by using reversible thermochemical processes.

There is a wide range of reactive pairs: more than two hundred thermodynamic data on reactive salts have been indexed in our database. The thermal range of these reactions varies from -30°C to 300°C . A selection of suitable reactive pairs enables to adjust the operating temperature of a process to a given application. The large possibility of reactive pairs leads to a large panel of applications: freezing, refrigeration, air conditioning, hot water or vapor production.

Different types of thermal source can be considered: renewable geothermal or waste heat. Industrial thermal wastes from power stations or incinerators are of a great importance, and it seems to be a good way to explore here solutions for using them. In fact, each thermal source between 60°C and 200°C can be considered as a real potential that can be increased in value thanks to a long distance thermal transport. So, the global conversion process should make a better use of the primary energy and would be more respectful of the environment by reducing CO₂ production. Actually, below a low driving temperature level, electricity production from a heat engine becomes expensive, and so "valuable" thermal wastes are unavoidable. This economical statement leads to consider that a technical-economic analysis of any heat engine or power plant should be achieved in order to optimize electricity production and thermal transport. Thermal wastes that are produced in a remote area can thus be increased in value by implementing long distance heat transport process.

Solid sorption systems also enable a time-delayed production. As soon as the regeneration phase is finished, the production phase does not necessarily start. The time-delay varies from hours to days. Solid sorption processes are really adapted to intermittent source, such as solar heat.

According to the kind of physico-chemical process that is implemented, the useful heat production can be continuous (liquid/gas absorption) or discontinuous (solid sorption). Of course in this last case, a pseudo continuous functioning can be obtained by coupling several solid/gas reactors in opposite phase.

Remarkable points of the proposed concept lie in its multi-functionality and the diversity of thermal production : cold, heat, or cold and heat. Moreover, the advantage of such systems lies also in their specific utilization of thermal energy, more abundant and cheaper than the electric one.

Long-distance transport of thermal energy is the field of many researches, justified by the present energy crisis. Many gas-fired processes exist and use natural gas as energetic vector. Early studies started in eighties with a German project called ADAM-EVA. Using a reversible chemical reaction, their system needs a thermal source of 950°C [1]. Other studies deal with absorption processes like NH₃-H₂O or LiBr-H₂O [2] in order to produce cold at long distance. This last concept needs three pipelines, and therefore three circulating pumps. Other researchers studied processes based on hydrides [3]. These systems provide heat at 90°C thanks to a distant thermal source at 90°C. The efficiency of the transport process is 60% whatever the distance between user's location and source site is. Unfortunately in this concept, a thermal source is needed on the user site at 70°C. Other economical studies [4] have estimated the benefit of using a sorption cycle in comparison with latent or sensible heat transport. As soon as the distance between consumers and suppliers increases (more than 5 kilometers), a transport process using reversible chemical reactions becomes promising.

2.2 Cascade cycle

A better concept than this classic simple effect process was patented by our laboratory [5]. An innovating system based on thermal cascades has been proposed by coupling several thermochemical dipoles as shown in figure 2 [6].

EC1 is on the source site and EC2 on the user site. In one phase, the thermal source allows to liberate Gas1 from EC1. Then, an exothermic reaction can take place in R1 and this reaction provides the required heat for the endothermic reaction that occurs in R2. Thus, Gas2 flows to user site and produces the useful heat (transported heat) thanks to its condensation in EC2. In the other phase, the low temperature heat demand on user location (EC2) produces cold and makes flow the reactive Gas2. The exothermic reaction in R2 allows the endothermic reaction in R1. The first gas Gas1 returns to source site in reactor EC1. For the equivalent heat production, the simple effect sorption cycle would be composed of R2 and EC2 using Gas2.

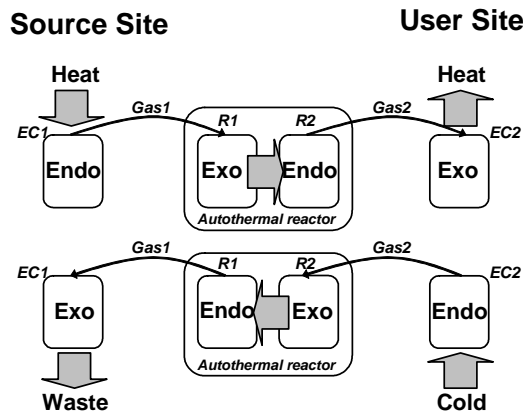


Figure 2: An innovating system based on thermal cascades.

The transported gas can either be Gas1 (connection between EC1 and R1) or Gas2 (connection between EC2 and R2). The choice depends on the nature of the gas and the pressure transport. The system pressure has to be higher than atmospheric pressure but also not too high for mechanical resistance reasons.

As shown on figure 2, there is an original coupling between the two reactors R1 and R2. They continuously exchange their thermal energies without external heat source. This kind of coupling constitutes an “autothermal reactor”. For example, in a first phase, gas absorption in reactor R1 provides energy for gas desorption in R2. In the second phase, gas desorption in reactor R1 consumes the energy of absorption occurred in R2. Moreover, this reactor can be designed with a constructal approach for an efficient energy management. This multi-scale conception of reactor allows supplying a very wide range of power.

There are several reasons that give a particular interest of such a system based on thermal cascades:

- *Heat upgrading applications:* for a simple effect cycle, heat is produced on user site at a temperature lower than the heat source temperature (respectively at C2 and D2, for the simple effect Gas2-Salt2 fig.3). Contrary to a simple effect cycle, the cascading cycle allows heat upgrading. The temperature of heat production on user site (at C2) can be higher than the temperature of heat supplied by the industrial source site (at E1, fig.3). It seems to be the only system that enables to upgrade heat available at long distance site. Generally, heat transport leads to a decrease in temperature levels. By using a cascaded sorption process, heat production at user site can be provided at a higher temperature than that available at the source site.

- *Required source temperature:* the source temperature of the simple effect system corresponds to the decomposition temperature T_{D2} of Salt2. For the cascade process, the source temperature is the one that corresponds to the evaporation temperature T_{E1} of Gas1. So, the required heat source temperature can also be significantly reduced.
- *Energetic efficiency:* The energetic efficiency (COP) of thermochemical process depends on reactive pairs that are used. Moreover, liquid/gas transformations have generally an enthalpy twice lower than one of solid/gas reaction. Ideal efficiency of simple effect cycle is around 0.5 (useful effect in condenser/needed source for reactor). With a thermal cascade, an evaporator can be the energy consumer component (E1, fig.3). For the same reactive gas (Gas1=Gas2) and a perfect autothermal reactor, cascade process can have an ideal efficiency of 1 (useful energy at C2/ consumed heat at E1). Indeed, the greater complexity of this process should penalize the real efficiency.

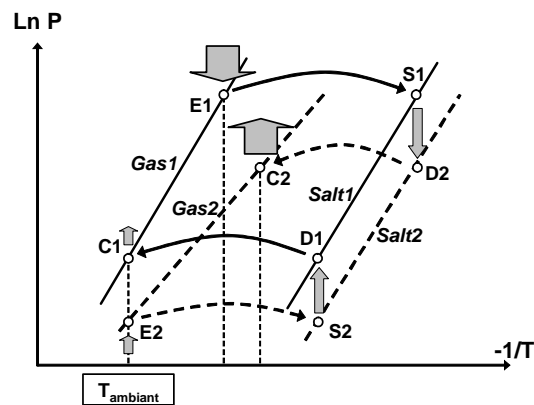


Figure 3: Cascaded cycle in order to realize a heat upgrading (Clausius-Clapeyron diagram).

2.3 Example of cascaded cycle

Figure 4 presents an example of process that couples two thermochemical dipoles for a long distance cold production application. The reactive salts are a hydrate $MnCl_2 \cdot 1/0H_2O$ and an ammoniate $NiCl_2 \cdot 6/2NH_3$. Only the evaporator E2 is far away localized on user site. The transported gas is ammonia. This concept, which is applied here to well-known reactive pairs, could be extended. The regeneration phase is the high pressure one of the system. The heat source available at $140^\circ C$ allows to evaporate water in E1. The hydrate synthesis S1 that occurs in R1 produces energy at $270^\circ C$. Then, the decomposition D2 of the ammoniate can happen (at $260^\circ C$). The gaseous ammonia is condensed at $20^\circ C$ on the industrial site. Liquid ammonia is transported to user site (under 10 bars). For energetic and practical reasons, a liquid phase transport is better and avoids condensation along pipelines. In low pressure phase (production one), the evaporation of ammonia under 1 bar produces freezing effect at $-33^\circ C$. The gas flows until the industrial site where it is absorbed by the ammoniate (synthesis S2). The resulting heat is supplied to D1 in order to make the decomposition of the hydrate. Steam leaving the reactor D1 is finally condensed at $30^\circ C$ in the industrial site. The ideal COP is 0.60 for this example. The source temperature ($140^\circ C$) may come from industrial wastes. For a simple effect cycle that uses $NiCl_2$ and NH_3 , the

temperature of the needed heat source would be more important (260°C) for producing the same useful effect, and the ideal COP would be smaller (0.39). The ideal performances of thermal cascade process adapted to a distant refrigeration application, are higher than simple effect system.

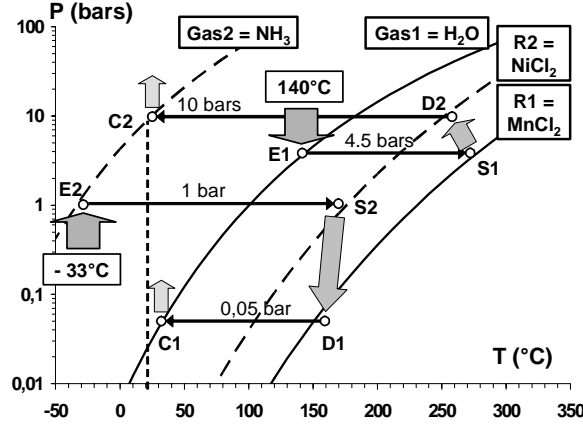


Figure 4: Example of cold production at -33°C thanks to a thermal source away of 140°C.

3. Cost of transport

For the studied thermochemical system, there are no thermal losses on along the transport pipeline. The only transport losses result from pressure losses in the pipeline. These pressure losses can be differently managed: either they are compensated by a compressor (energetic impact), either they are integrated into the temperature operating conditions (functioning impact).

The following study will carry out a cost estimation of transport in the case of cold production application.

3.1 Energetic impact

In steady state, for a fixed cold production and a fixed pipe diameter, the gas flow velocity u in the pipeline can be evaluated thanks to the cooling transported power:

$$P_c = \rho \frac{\pi d^2}{4} u \Delta h_{\text{vap}} \quad (1)$$

In the conditions of figure 4, with one meter diameter for gas pipelines (at low pressure), with 20cm diameter for liquid pipelines (at high pressure), and for a cold power ranging from 1MW to 10MW, velocities do not exceed 15m/s for the gas and 1m/s for the liquid. For power higher than 10MW, pipelines should be larger ($d_G=1.5\text{m}$ and $d_L=30\text{cm}$) in order to maintain acceptable flow rates.

So, for a given transported power, the regular pressure losses in a smooth tube are calculated according to flow regime [7].

$$\Delta P = \lambda \frac{L}{d} \frac{\rho u^2}{2} \quad (2)$$

Then, the energetic cost of compressor and pump (eq. 3) allows determining the new overall COP (eq. 4). This new efficiency takes into account the mechanical energy that

is consumed for the transport of fluids (assuming incompressible fluid and isentropic transformations).

$$P_{\text{comp}} = \Delta P \rho \frac{\pi d_G^2}{4} u_G \frac{1}{\eta_{\text{comp}}} \quad (3)$$

$$\text{COP} = \frac{P_C}{P_S + P_{\text{comp}} + P_{\text{pump}}} \quad (4)$$

Figure 5 presents the influence of pressure losses on COP as a function of the cold power and for several pipeline lengths (10km and 100km). These lengths represent the user/source distance including the equivalent length of singularities (elbows, valves...). In this example, the ideal COP of the cascaded process, which produces 10MW of cold 100km away, decreases from 0.6 to 0.57. For a larger installation, pipeline diameter should be greater in order to maintain acceptable pressure losses.

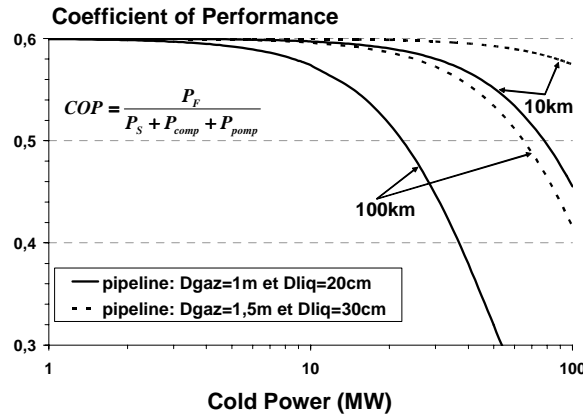


Figure 5: COP evolution as a function of cold powers and distances.

3.2 Operating impact

Another possibility consists in modifying the operating temperature level of the process in order to avoid the use of a compressor to compensate the pressure losses. In particular, concerning the gas transport between E2 and S2 (fig. 6), the initial pressure in E2 should be higher in order to compensate pressure losses into the pipeline. So, the temperature level of really produced cold would be higher than that corresponding to the ideal isobaric case of -33°C (fig. 4).

Nevertheless, the increase in the cold temperature for different distances and powers, drawn on fig. 6, remains acceptable. For example, the cold temperature becomes -22°C instead of -33°C, in the case of 100km remote distance and 10MW cooling power.

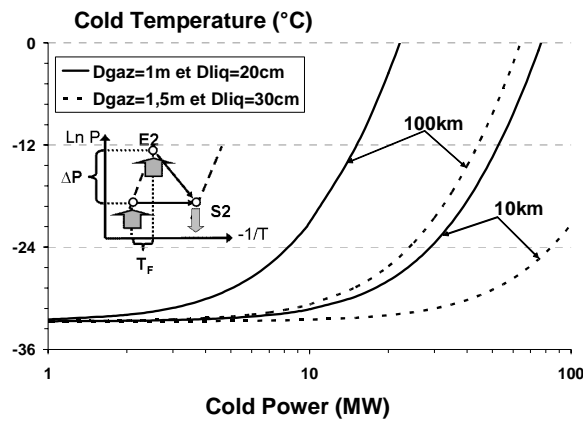


Figure 6: Cold temperature evolution as a fonction of cooling power and transport distances.

4. Comparison between two processes of cold transport

The aim is to compare performances between two processes of cold transport for air conditioning applications. The first one consist of a cold production process on industrial site and a transport of the chilled water and the other one is the proposed cascaded process (fig. 4). In both cases, cold is produced at 10°C by using a thermal source of 140°C. In order to focus on thermal aspects, the pipelines are designed so that mechanical losses (compression or/and pump) are the same for each fluid (pressure losses of $\Delta P=0.1\text{bar}$). Thus, for given cold power or fixed distance, the thermochemical process needs a smaller pipeline diameter (tab.1).

<i>cooling power</i>	1MW			10MW		
fluid	<i>chilled water</i>	$NH_{3,G}$	$NH_{3,L}$	<i>chilled water</i>	$NH_{3,G}$	$NH_{3,L}$
L=5km	0,345	0,232	0,097	0,807	0,543	0,227
L=20km	0,463	0,311	0,130	1,080	0,727	0,304
L=100km	0,649	0,437	0,183	1,516	1,020	0,427

Tableau 1: Required pipeline diameter (m) in order to obtain a maximum pressure loss of 0.1 bar.

In the case of chilled water, the thermal losses and the produced cold temperature on industrial site, in order to supply 10°C on user site, are determined thanks to relations 5 and 6. Here, only the thermal resistance of isolation (2cm of polyurethane) is taken into account.

$$P_{\text{therm}} = \rho \frac{\pi d^2}{4} u c_p \Delta T \quad (5)$$

$$P_{\text{therm}} = \frac{\lambda_{\text{th}}}{e} \pi d L \Delta T_{\text{log}} \quad (6)$$

The first hypothesis is that the real COP for the process that produces the chilled water is 0.6. For the sorption cascaded process (fig.4), although the ideal COP is 0.6, the practical COP that can be achieved is only 0.3 because of thermodynamic irreversibilities.

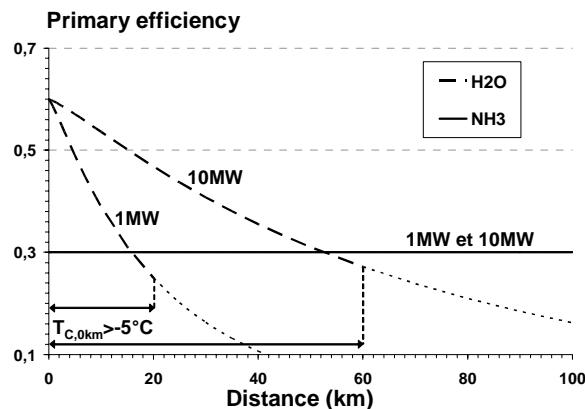


Figure 7: Comparison of primary efficiency between a chilled water network and a thermochemical process as a function of the transport distance ($T_C = 10^\circ\text{C}$, $T_S = 140^\circ\text{C}$).

The primary efficiency of these processes is defined as the ratio between the useful energy at 10°C and total consumed energy (heat consumed on industrial site at 140°C and mechanical energy needed for fluid transport). Figure 7 shows the negligible impact of the pressure losses on the efficiency of thermochemical process: for any distance or any cooling power, the efficiency nearly stays constant at 0.3. In contrary, for chilled water networks, the efficiency drastically decreases with the distance. Thus, the chilled water networks stay efficient for short distance transportation despite the pipeline is larger (tab.1). Moreover, the starting temperature of the chilled water on the industrial site should reach a too low temperature level (dotted lines on figure 7 for $T_{C,0km} < -5^\circ\text{C}$) in order to compensate the thermal losses. The thermochemical process seems to be very efficient for high production power (small pipeline diameter) and for long distances (primary efficiency nearly independent of distance). In this comparison, it is important to note that the cascaded process is not in its optimal configuration: the process can produce cold down to -33°C .

5. Conclusion

The concept based on thermochemical cycles allows envisaging long-distance transport of thermal energy. The originality of this work lies in the use of several thermal cascades. Three positive points of this system are the heat upgrading, reduced driving temperature of the heat source and a better ideal efficiency. Concerning the pressure losses, whatever the solution (mechanical compression or operating management), the transport cost is acceptable. The comparison between two processes of cold transport shows that thermochemical process is highly efficient for long distance and high power. This work will go on with a process simulation in order to evaluate its performances in practical conditions. A prototype realization is also in progress in order to understand some key points of the system.

Acknowledgements

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