Comparative assessment of processes for the transportation of thermal energy over long distances

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Industrial waste heats represent a huge amount of thermal energy, which is usually located several tens kilometers away from potential users (district heating, food-processing industry...). Therefore, the transportation of heat over long distances (over 10 km) represents a real scientific and technological challenge for a better and sustainable management of the energy resources.

Since the 70', several research projects focus on this research area. The basic idea is to implement a thermochemical process between the source and user sites, in order to replace the transportation of thermal energy by the transportation of an active fluid (a reactive gas for example) at ambient temperature. As a result, the thermal losses due to the transportation are low, and transportation over long distances can be considered.

1. Thermochemical processes for transportation of thermal energy

Processes involving thermochemical transformations can be relevant for such purposes. The transformations can be ab- or ad-sorption, chemical reaction, phase change... For example, such a thermal energy transportation process based on solid-gas reactions involves two solid gas reactors, one on the source site and the other on the user site, coupled by the transportation of the reactive gas between them (figure 1). On the source site, an endothermal decomposition takes place, releasing the reactive gas, which then flows to the user site where it is involved in an exothermal reaction. Such solid gas reactions are reversible, and reversing both reactions (using a free low temperature source on the user site) allows the gas to flow back to the source site. As the gas is transported at ambient temperature, the source-to-user distance less affects the energy transportation efficiency.

Moreover, such thermochemical systems allow producing several functionalities on the user site: cold production or heat production or heat upgrading. This multifonctionnality is a really innovative characteristic of this concept.

Such systems based on solid-gas thermochemical processes are investigated at CNRS-PROMES since a few years [1-3]. We have thoroughly studied several concepts of cycles (single effect or cascade) fulfilling the requirements of the transport of thermal energy, and the potentialities of these concepts according to the reactive pairs.
2. Comparative assessment

Now, the performances of these systems have to be evaluated, and to be compared with classical processes of energy transportation (i.e. electricity network coupled with heat pump, transport by coolant (sensible heat) or slurries (latent heat)).

For this assessment, all the systems are driven by heat released from the source site at a given temperature and all of them produce the same utility on the user site.

A general method has to be developed to assess the performances of all these paths of energy transportation on the same basis, whatever the form of the transported energy is (chemical, mechanical…). Thermodynamics offers such a tool, especially exergy analysis.

All these processes can be divided in three sub-systems (figure 2): two ‘exergy converters’, coupled to the exergy transportation network. Each sub system is characterized by exergy efficiency or exergy destruction:

- the converter on the source site converts the waste heat in a flow \( n \) of an extensity (electrons, gas, liquid, solid),
- the transportation network, which transports this extensity through one or several pipes to and from the user site, involving some exergy losses,
- the converter on the user site which produces the useful heat or cold.

Fig. 2. Generic scheme for thermodynamics analysis of energy transportation.

Then, the overall exergy efficiency \( \eta_{\text{ex}} \) and the overall energy efficiency \( \varepsilon \) can be easily deduced:

\[
\eta = q_s \left[ \frac{1}{w_s} \right] \eta_{\text{ex}} \quad \varepsilon = \frac{q_s}{q_s} = \eta_{\text{ex}} \left( 1 - \frac{T_u}{T_s} \right) \left( 1 - \frac{T_u}{T_s} \right) \quad (4)
\]

- Assumptions for systems under study

The systems under study are described in figure 3.

Fig. 3. Energy transportation systems under study. *Transport of: a) electricity, b) coolant, c) slurry, d) reactive fluid.*
They are all fired only by a heat source at $T_S$. If mechanical energy is required (for pump for example), it is produced by a converter using the same input thermal source. Two cases are investigated: $T_a$=100°C or 400°C.

All these systems provide the same cold utility on the user site. Thus, the user site operating conditions are fixed as: $T_a$=8°C, $T_{a_s}$=12°C, $q_u$=20 MW.

- according to industrial standards, we assume that all the thermodynamic converters (motor, heat pump or thermochemical reactor converting heat to electricity, electricity to heat or cold, or heat to cold) have the same exergy yield: $\eta_{el} = \eta_{ch} = 0.4$
- the heat exchangers effectiveness is $\varepsilon=0.8$, and their energy yield is $\varepsilon=1$ (no thermal losses);
- the reference temperature for the exergy analysis is $T_e=T_{ext}= 35^\circ C$ in summer.
- the energy efficiency of the transport of electricity by extra-high voltage transmission lines is $\eta_{hv}=0.97$, and the efficiency of the conversion from extra-high to low voltage is $\eta_{hv/lv}=0.9$.
- For the transport lines of coolants, typical values of roughness ($r=0.1\ mm$) and liquid velocity ($u=3\ m/s$) are used to estimate the pressure drop during the transport. The pipe diameter is deduced from $u$ and $q_{hv}$. For the slurry network: a ice/ethanol slurry which has been used (alcohol mass ratio is $w_a=10\% = \Rightarrow$ freezing temperature $=-4^\circ C$), and its ice mass ratio must be lower than $w_i=40\%$.
- For the thermochemical process: one advantage of this system lies in the possibility of using the pressure difference between the condenser and the evaporator to drive the liquid flow to the user site. Therefore, we fixed the pressure drop $\Delta p = p_1 - p_1^*$, which maximal value is the available pressure drop $\Delta p_{max} = p_{cond} - P_{cond}$. Then, the liquid velocity and pipe diameter can be deduced from $\Delta p$ and $q_{hv}$. For the back flow gas line, the pressure is bounded by $p_{sat}(T_{evap})$ on the user site, and by the pressure of the synthesis reaction that occurs in the reactor on the source site: $p_{synthesis}=p_{eq}(T_{as})+ \text{Dp}_{eq}$. $Dp_{eq}$ is the equilibrium drop required for the reaction. So, for this line, we get $\Delta p_{max} = p_{evap} - P_{synthesis}$.

Heat losses are neglected as the fluid is supposed at the constant temperature of the soil ($20^\circ C$) all along both pipes. The reactive pair is BaCl$_2$/NH$_3$, whose thermodynamic data are well known.

- **Results/Discussion**

Figure 4 compares the exergy yields vs. the transportation distance for these four energy transportation processes described in figure 3.

**Fig. 4. Exergy yields for the four processes investigated for the transportation of energy**

Thus, compared to electricity network, the transport of sensible or latent heat is relevant only for distances lower than about 10 km. On the other hand, a thermochemical process is relevant for the wider range of distance. As the transportation of the reactive fluid is driven by the existing pressure difference between the condenser and the evaporator, this system can work without any additional exergy destruction due to the transport.

Complementary information is given by the analysis of the exergy destructions in each part of the energy transportation system. They are defined as follows:

- **source site**
  
  $$ex_{s} = q_{s}T_{s} - ex$$

- **transportation**
  
  $$ex_{t} = ex - ex$$

- **user site**
  
  $$ex_{u} = ex - ex$$
Then, the number of exergy destruction N is defined as the ratio of the destroyed exergy to the inlet exergy \( e_{x_S} \). As the exergy efficiency of the converters on the source site is fixed (\( \eta = 0.4 \)), this part of the exergy destruction is the same for the three systems: \( N_S = 0.6 \). The number of exergy destruction resulting from the transport and the conversion on the user site are plotted in figure 5. It shows that the user site has a moderate effect, as it involves less than 10% of the exergy destruction for all the systems. The transportation has a more important effect, and it exhibits a significant difference between systems based on a coolant or slurry and on a reactive fluid.

For example, for 20 km, the part of exergy destruction related to the transport is 5.9% for thermochemical systems, and more than 25% for the two others systems. Moreover, as the inlet exergy \( e_{x_S} \) is also lower for thermochemical systems (as highlighted by the higher exergy yield, figure 4), the resulting exergy destruction due to the transportation \( e_{x_T} \) is much more lower for thermochemical systems.

The last comparison deals with the flowing conditions for the 3 processes involving liquid or gas flows, which are summarized as follows:

<table>
<thead>
<tr>
<th></th>
<th>flow to user</th>
<th>flow to source</th>
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<tbody>
<tr>
<td>coolant</td>
<td>( u_{iq}=3 \text{m/s}, \ d=0.61 \text{m} )</td>
<td></td>
</tr>
<tr>
<td>slurry</td>
<td>( u_{iq}=3 \text{m/s}, \ d=0.35 \text{m} )</td>
<td></td>
</tr>
<tr>
<td>reactive fluid</td>
<td>( u_{iq}=0.5 \text{m/s}, \ d=0.27 \text{m} ) ( u_{ga}=2.5 \text{m/s}, \ d=0.12 \text{m} )</td>
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Thus, the thermochemical process presents a significant advantage regarding the civil engineering required for the network.

- References at PROMES

