Dual Media Thermocline (DMT) techno-economic interest for heat storage on the range 80°C –600°C – The SMARTREC project

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Abstract. The economic assessment of a sensible heat storage system, the Dual Media Thermocline (DMT), is estimated for an industrial application of waste heat storage on the range of temperature 80°C to 600°C. The DMT is a main component of the standard and modular system developed in the frame of the H2020 Smartrec project (GA n° 723838). Further, the life cycle assessment (LCA) of the 1MWh Smartrec system is studied.

1 Context

Waste heat is a common problem to all processing industries. While low temperature waste heat valorisation is a real challenge, medium to high temperature waste heat can be easily re-used inside the industrial process thanks to a better integration of the heat fluxes. This leads to a reduction of energetic costs and carbon footprint of the process. For some industries, such as, secondary aluminium recycling or ceramic processing, it is more challenging because the processes are batch-based rather than continuous and the waste heat is mainly contained in the corrosive particulate-laden flue gas that exit the industrial ovens at a temperature varying between 200°C and 1000°C depending on the processes.

A standard and modular solution meeting these challenges is developed in the frame of the H2020 Smartrec project (GA n°723838), also referenced as the ‘Smartrec’ system. The main innovating components of the system are a heat pipe heat-exchanger (HPHE) that recovers the waste heat on the flue gas while minimizing the corrosion and fouling effects and a storage system (DMT) that converts an intermittent heat flux from a batch process into a continuous heat flux delivered on the end-user side, the range of temperature varying from 80°C to 600°C according to the processes.

The present article will focus on the storage system and will detail its economic interest. Then a life cycle analysis of the 1 MWh Smartrec system will be presented.

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2 Storage principle and integration in the process

Heat can be stored in three different ways, sensible, latent or chemical storage [2]. Sensible storage is already industrial at large scale, such as water storage for district heating networks, two-tanks of molten salt on solar concentrated power plants or ceramic regenerators on glass manufactures whereas the 2 other methods are less mature.

Compared to two-tank systems, thermoclines are more innovative and less expensive [3, 4] because the hot and the cold fluids are stored in a single tank separated by a thermal gradient or ‘thermocline’. The reservoir can be moreover filled with a solid structure, limiting the amount of fluid when it is expensive, in that case the storage is a Dual Media Thermocline storage (DMT).

During the phase of heat storage, the hot heat transfer fluid (HTF) is fed at the top of the storage unit and flows down through the packed bed of solid material, heating up progressively the solid filler layers. The HTF flows out cold. The unit is fully charged when the bottom layers start to heat up. The heat discharge is done by reversing the HTF flow. The cold flow is fed at the bottom of the bed and moves up, the solid filler releases slowly its sensible heat and heats up the HTF that goes out hot. The discharge stops when the upper layers of solids start to cool down. In a process unit, the storage system is generally linked in parallel to the heat generator and the power block, especially when a steady power is required.

Fig. 1. DMT integrated in the process, charge and discharge modes.

3 DMT economic interest

3.1 Cost model

The DMT cost model developed under Matlab is valid on a large range of energies, 100 kWh – 1 GWh, and a large range of temperature, 80–600°C, and limited to above-ground metallic DMTs. The model is based on the ‘pre-estimate’ method, part ‘Tank’ developed for the petroleum industry [5]. Thanks to a DMT thermohydraulic model, the size of the tank is calculated, then the thickness of the walls – which is related for a specific alloy to the tank diameter, temperature and pressure- and the weight of the tank. The correspondent cost can be then calculated thanks to corrective shape factors coefficients, a large vessel being relatively cheaper than a small one. When the cost of the bare tank has been evaluated, the cost of the whole system, ready for operation can be calculated by affecting a percentage for other materials such as pipes, valves, instrumentation or insulation (63%), on site assembly

(58%) and indirect costs on work site (77%). The percentage values are given for the year 2000 and must be corrected for another year using the Chemical Engineering Plant Cost Index (CEPCI).

The cost of HTF, solid filler, transport and filling procedure have to be evaluate separately. Quotations were done for the solid and HTF materials. Transport cost was evaluated on the basis of the load to transport and the cost of a single transport. The solid filling cost is based on the number of days for filling. Apart from the materials themselves, the transport and filling costs are thus approximate but low. Fig. 2 details the main costs of a DMT with HITEC as HTF and quartzite as solid filler and the global cost of the DMT system installed, filled and ready for operation.

Fig. 2. DMT costs details – Transport and filling costs are close to zero.

Fig. 3 gives an overview of different DMTs cost (in €/kWh) for 2 sizes (400 kWh and 400 MWh). To allow comparison, the costs are calculated for a unique difference of temperature of 200°C for all systems, which is detrimental for Solar salt for instance or air that can have a higher difference.

We observe a sharp reduction of the DMT cost between 400 kWh and 400 MWh. The tank itself represent a high percentage of the DMT cost, which explains why the cost tends to increase when he temperature increase as the metal alloy is more expensive. Adding sand to the main solid filler decreases the bed porosity and HTF volume, and has an effect on the cost if the HTF is expensive (HITEC, Therminol 66). Pressurised water thermoclines are very competitive for low temperature storage and low energy but loose this advantage at large scale because the economy of scale is not as effective as the modules have a maximal storage energy of 20 MWh each. Air is also competitive at high temperature and small scale because the HTF is costless, still we have to keep in mind the OPEX costs of air compression. Thermal oil DMTs are less expensive than molten salt ones at small scale but loose this advantage at large scale because the cost of thermal oil does not decrease very much when bought in large quantities. DMT with HITEC salt and quartzite is the more expensive system at low scale because the HITEC salt is expensive and the melting costs must be added, but the system has an interesting cost of 32.5 €/kWh at large-scale.

Fig. 3. Cost in €/kWh of different DMT systems with a storage DT of 200°C on the range 50–550°C (NB: water pressurised DMT modules have a maximal energy of 20MWh, there are 20 modules for 400 MWh).

3.2 Return on Investment (ROI)

To estimate the time in years that separate an investment to the cumulated benefit of the same amount or ROI (Return on Investment) of a DMT storage system, we consider that the recovered waste heat is costless and will displace natural gas in the industrial process. The CAPEX costs are amortized over 20 years, the OPEX cost represent 1% of the CAPEX cost every year and the discount rate is 5%.

Natural gas has an average cost free of taxes of 28 €/MWh_{GCV}[†] but this cost is submitted to increasing CO₂ taxes, we expect that the price of Natural gas on the period 2018–2038 will be 45.31 €/MWh_{GCV} for low CO₂ scenario and 53.49 €/MWh_{GCV} for high CO₂ scenario.

Fig. 4. Evolution of ROI with the number of charge and discharge cycles per year for a 400 kWh (left) and a 400 MWh (right) DMT – HITEC salt, quartzite, sand, 200–400°C.

The ROI depends on the number of cycles of the DMT charge and discharge per year. Fig. 4 highlights that a ROI lower than 5 years can be reached if the number of cycles are higher than 750 to 880 for a 400 kWh DMT and 125 to 150 for a 400 MWh DMT, in the case of HITEC salt-quartzite-sand. As expected large DMTs can have an economic interest even with a single storage cycle per day whereas small-scale DMTs should be cycled several times each day to be competitive.

[†] Gross Calorifique Value

4 LCA analysis of the 1 MWh Smartrec system

The Smartrec system is mainly a combination of 200 kW HPHE and 400 kWh DMT subassemblies along with ancillary instruments, piping system, end user heat exchanger (HX), to provide a constant load of 100 kW thermal energy to the end user HX utilising intermittent waste heat source. For LCA study, life cycle inventory (LCI) data were collected from primary [6, 7] and secondary sources. The secondary data comes from literature sources, being specific to either a product, material or process in question. For those processes, secondary data were lacking, modelled data or assumptions were served as defaults. All the collected data was normalised to the study functional unit of 1 MWh of Smartrec system and then imported into SimaPro 8.5.2.0, a commercially available LCA tool which stores and organises life cycle inventory and calculates the environmental impacts for the product profile of 1 MWh Smartrec system [8].

Tables 1 and 2 list the life cycle inventory (LCI) data of materials, energy flows, and transportation in terms of functional unit of 1 MWh with dataset name used for LCA studies for 200 kW HPHE and 400 kWh DMT subsystems, respectively. The total thermal energy recovered by 200 kW HPHE and stored and delivered by 400 kWh DMT during their 20 years of lifetime with 10% downtime is 7884 MWh.

Different materials, energy flows and transportation involved during use phase of the Smartrec system and listed in Table 3.

Table 1. Materials, energy flows and transportation used for 200 kW HPHE subassembly system.

Items	Amount used for 200 kW HPHE	Functional amount	Dataset name
Carbon steel (kg)	623	0.0790	Steel, low-alloyed {GLO} market for APOS, U
304 stainless steel (kg)	1850	0.2347	Steel, chromium steel 18/8 (GLO) market for APOS, U
Distilled water (kg)	127	0.0161	Water, ultrapure {GLO} market for APOS, U
Electrical energy (kWh)	549.56	0.0697	Electricity, medium voltage, (GB) market for APOS, U
Transportation (km)	520	0.0660	Transport, freight lorry 16–32 metric ton, EURO6

It is noted that the maintenance frequency of Smartrec system is twice in a year. At the end-of-life stage, the whole assembly of Smartrec system is disassembled first, then 80% of carbon steel and 304 stainless steel materials goes for recycling and the rest of them goes for waste disposal treatment.

The Life Cycle Impact Assessment (LCIA) methodology used in this LCA study is the IMPACT2002+ V2.14 / IMPACT 2002+ which is compliant with the ISO 14040 series. The IMPACT 2002+ LCIA methodology [9] proposes a feasible implementation of a combined midpoint and damage approach, linking all types of Life Cycle Inventory results (elementary flows and other interventions) via 15 midpoint categories to 4 damage categories (endpoint level categories): human health, ecosystem quality, climate change and resources. Using the data described in tables 1, 2 and 3, we have modelled the 1 MWh Smartrec system for recovering and delivering of 100 kW_t useful heat energy every hour through SimaPro8.5.2.0.

Once the model is ready, we can easily iterate LCA results of 1 MWh Smartrec system in terms of climate change impact category in units of kg CO₂ eq. and other damage categories. In the use phase of the assembly Smartrec, it does not need any fuel instead it uses waste flue gas to generate 1 MWh of heat energy. If we consider the fuel as coal, then the amount of energy needed to produce 1 MWh of heat energy using avoided products of coal with 85% efficiency is 1.18 MWh. The amount of coal needed to generate that 1.18MWh of heat energy is about 212.4 kg, considering the coal has a heat value of 20,000 kJ kg⁻¹ [10].

Table 2. Materials, energy flows and transportation used for 400 kWh DMT subassembly system.

Items	Amount used for 400 kWh DMT	Functional amount	Dataset name
Carbon steel (kg)	2599	0.3296	Steel, low-alloyed {GLO} market for APOS, U
Quartzite (kg)	12000	1.5221	Gravel, round {CH} market for gravel, APOS, U
Hitec (kg)	7000	0.8879	53% Potassium nitrate {GLO} market for APOS, U; 40% Sodium nitrite {GLO} market for APOS, U; 7% Sodium nitrate {GLO} market for APOS, U
Rock wool (kg)	600	0.0761	Rock wool {CH} production Conseq, U
Electrical energy (kWh)	1040	0.1391	Electricity, medium voltage, (GB) market for APOS, U
Transportation (ton.km)	5360	0.6799	Transport, freight lorry 16–32 metric ton, EURO6

Table 3. Different materials and processes involved during use phase of Smartrec system.

Items	Amount used for lifetime of Smartrec system	Functional amount	Dataset name
Water (kg)	20,000	2.5368	Water, decarbonised, at user {GLO} market for APOS, U
Chemicals (sodium hydroxide) (kg)	2,000	0.2537	Sodium hydroxide, without water, in 50% solution (GLO) market APOS, U
Electrical energy of preheating the Hitec, DMT tank, pipes and quartzite (kWh)	82,024	10.4	Electricity, medium voltage, (GB) market for APOS, U
Electrical energy consumed by the pump (kWh)	126,144	16	Electricity, medium voltage, (GB) market for APOS, U
Transportation (ton.km)	4400	0.5581	Transport, freight lorry 16–32 metric ton, EURO6

Table 4 lists the LCA results of four damage categories of environmental impacts by the Smartrec system for the functional unit of 1 MWh. All four damage categories presented positive environmental impacts for 1 MWh thermal energy output through the Smartrec

system. The 200 kW HPHE system contributes large positive environmental impacts in resources, climate change and ecosystem quality damage categories since it uses costless waste heat flue gas as a fuel instead of coal or other non-renewable fuel. The overall climate change category impact of the 1 MWh Smartrec system is about -10.5 kg CO₂ eq.

Table 4. LCA results of the Smartrec system for the functional unit of 1 MWh in four damage categories.

Damage category	Unit	Total	1 MWh Smartrec System	200kW HPHE	400kW DMT	End-of-life Wastes of Smartrec system
Human health	DALY	-4.6x10 ⁻⁵	6.2 x 10 ⁻⁶	-5.7 x 10 ⁻⁵	5.2 x 10 ⁻⁶	2.5 x 10 ⁻⁷
Ecosystem quality	PDF·m ² ·yr	-8.5	1.9	-12.6	1.8	0.32
Climate change	kg CO ² eq	-10.5	4.3	-26.2	9.8	1.5
Resources	MJ primary	-1844	54	-2066	140	28

5 Conclusion

The Smartrec system is a standard and modular solution for waste heat recover on industrial processes that is developed in the framework of the H2020 Smartrec project (GA n°723838). The main components are a heat pipe heat exchanger (HPHE) that recovers waste heat and a heat storage module (DMT) that convert intermittent waste heat in a continuous flux on the end-user side.

In this paper, a cost model of the DMT is presented and provides the cost in €/kWh for various storage modules on a wide range of temperature (80°C–600°C) and scales (400 kWh and 400 MWh). In the case of costless waste heat displacing natural gas in the industrial process, ROI lower than 5 years can be reached if the number of cycles of charge and discharge are high enough. As expected large DMTs can have an economic interest even with a single storage cycle per day whereas small-scale DMTs should be cycled several times each day to be competitive.

A 1MWh Smartrec system contributes a net savings of 8300 kg CO₂ eq. per year. The environmental impacts of 1 MWh Smartrec system in all damage categories is positive, where resources is contributing the most and human health is affected the least.

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