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Lock-in Amplifiers up to 600 MHz





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Heat Recovery at High Temperature by Molten Salts for High Temperature Processing Industries

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Abstract. Waste heat is a problem common to high temperature processing industries as a significantly underused resource, often due to challenges in economic heat valorization. Secondary aluminum recycling and ceramic processing were identified as key examples with economically recoverable waste heat. Several challenges are inherent; these processes are batch-based rather than continuous with corrosive particulate-laden flue gas over a wide temperature range. The EU H2020 Smartrec project aims to develop a technology capable to recover heat at high temperature from industrial processes. It is being coordinated by UK-based company ALTEK, with the rest of the consortium being made up of companies from EU countries. The Smartrec project is aimed at developing a modularized standard heat recovery solution integrated with thermal energy storage (TES) and a knowledge-based software tool. Smartrec has been designed for industrial applications such as secondary aluminum (furnace), ceramic (kiln), cement (kiln) and flat glass (furnace) industries with a very harsh and corrosive environment.

The concept of Smartrec is based on the utilization of a Heat Transfer Fluid (HTF) stable at high temperature ($\geq 600^{\circ}$ C) such as molten salts. Through a Heat Pipe Heat Exchanger (HPHE) the heat at the exit of heat source is transferred to the Heat Transfer Fluid (HTF) which is circulating within the Smartrec loop. When the input waste heat source is available, HTF will simultaneously transfer heat to the user end process via a user end heat exchanger (HX) or to a thermal energy storage (TES). When the exhaust stream is unavailable, the TES will supply the needed thermal energy to the HTF which in turn will transfer it to the user end Process via the user end HX.

The validation at industrial level of the abovementioned technology is currently ongoing as part of the Smartree project.

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INTRODUCTION

Energy efficiency in industries has improved significantly in the last decade, and one of the greatest opportunities for reducing energy use is waste heat recovery[1].

Industrial waste heat refers to energy that is generated in industrial processes without being put to practical use. Sources of waste heat include hot combustion gases discharged to the atmosphere, heated products exiting industrial processes, and heat transfer from hot equipment surfaces (Tab.1). The exact quantity of industrial waste heat is poorly quantified, but various studies have estimated that as much as 20 % to 50 % of industrial energy consumption is ultimately discharged as waste heat. While some waste heat losses from industrial processes are inevitable, facilities can reduce these losses by improving equipment efficiency or installing waste heat recovery technologies. Waste heat recovery entails capturing and reusing the waste heat in industrial processes for heating or for generating mechanical or electrical work (Tab.1). Example uses for waste heat include generating electricity, preheating combustion air, preheating furnace loads, absorption cooling, and space heating[2].

Heat recovery technologies frequently reduce the operating costs for facilities by increasing their energy productivity. Many recovery technologies are already well developed and technically proven; however, there are numerous applications where heat is not recovered due to a combination of economic and technical barriers, especially at high temperature where mechanical components and material constraints may impede a profitable installation.

Waste Heat Sources	Uses for Waste Heat
Combustion Exhausts:	Combustion air preheating
Glass melting furnace	Boiler feedwater preheating
Cement kiln	Load preheating
Fume incinerator	Load drying
Aluminium reverberatory furnace	Power generation
Boiler	• Steam generation for use in:
Ceramic kiln	power generation
• Process off-gases:	mechanical power
Steel electric arc furnace	process steam
Aluminium reverberatory furnace	• Space heating
Cooling water from:	Water preheating
Furnaces	• Transfer to liquid or gaseous process streams
Air compressors	
Internal combustion engines	
• Conductive, convective, and radiative losses	
from equipment:	
Hall-Hèroult cells ^a	
• Conductive, convective, and radiative losses	
from heated products:	
Hot cokes	
Blast furnace slags ^a	

^a Not currently recoverable with existing technology

TABLE 1: Examples of Waste Heat at High Temperature - Sources and End Uses[2]

Heat recovery at high temperature may allow a direct use of the recovered heat, this is always preferable due to the fact that the conversion of the thermal energy to electric energy is affected by a yield that entail an energy loss[3].

Smartrec Specifications and Applications

Smartrec is a modularised standard solution to recover and manage waste heat from corrosive, contaminated and intermittent exhaust streams. Smartrec is categorised based on the maximum operating temperature (T_H in Fig.1) related to the Smartrec loop. Based on this, there are three main types of Smartrec:

- Smartree Type 1: Smartree loop operating temperature ranging from 400°C-600°C. This type is best suited when the input temperature ranges from 500°C-1200°C and end user requirement is to recover waste heat of medium or high grade. Smartree type 1 will also be selected when the user has space constraints as this will ensure minimum size of the Dual-Media Thermocline (DMT) tank and optimum unit cost of thermal storage. Smartree type 1 is projected to be capable of recovering 60%-67% of the waste heat from the exhaust stream.
- Smartrec Type 2: Smartrec loop operating temperature ranging from 160°C-400°C. This type is best suited when the input temperature ranges from 200°C-500°C and end user requirement is to recover waste heat of medium grade. At lower temperature, the cost of the DMT will be higher due to the higher cost of HTF, but at the same time cost of the HPHE will be lower because in that case, low-cost material working fluid combination can be used to for the HPHE. Smartrec type 2 is projected to be capable of recovering 70%-75% of the waste heat from the exhaust stream.
- Smartrec Type 3: This is an extended version (not shown in the Fig.1) of Smartrec which will work at loop operating temperature ranging from 80°C-130°C. This type is best suited to when the input temperature ranges from 120°C-200°C and end user requirement is to recover waste heat of low grade. As at this operating temperature range, there is no feasible TES, so Smartrec type 3 will not have any DMT. The cost of Smartrec type 3 will thus be smaller. The cost of HPHE at this operating temperature is also low as in that case copper-water combination can be selected as the material working fluid combination to for the HPHE.

The functional model of Smartrec is described in Fig.1, where "DCS" stands for Distributed Control System.





END USER REQUIREMENTS

In the case of industrial heat recovery (HR) the end user requirement is related to energy efficiency and cost reduction; to increase overall efficiency it is necessary firstly to have the possibility to recover heat from a source, second there must be a need of re-utilization of that heat in the industrial process. It is also always possible to convert waste heat to power, in this case convenience must be verified; in case of positive evaluation customer requirement will be satisfied by an HR power plant. Typical end users are represented by ceramic, aluminium, cement, crystal and other industries where in the production process waste heat at high temperature is available.

End user requirements are therefore identified in OPEX (OPerating EXpenditure) reduction or in additional revenues from power generation. To get a complete figure of the Smartrec potential it is essential to know end user present energy costs in terms of electric energy cost [ϵ/kWh], fuels cost [ϵ/kWh], water cost [ϵ/m^3].

For these reasons the end user requirements can be satisfied by the identification and characterization of HR potential. Smartrec design requires input data from industrial site (customer); we classify these data in general and specific. General data inputs apply to all industrial site and determine the Smartrec standardization; specific data inputs refer to a single industrial site and determine the customization of Smartrec.

The following data are general inputs for Smartrec first design and dimensioning:

- 1. Waste heat heat source specifications
- 2. Heat valorisation
 - a. Heat requirement in the process (direct use of heat recovered);
 - b. Heat to power (indirect use of heat recovered).

Smartrec system has two main characteristics: it gives the possibility to recover heat at high temperature and to store heat turning a batch energy source into a continuous one. High temperature allows higher efficiency in power generation plants and a continuous heat source is more likely to be exploited in industrial processes.

Heat Source

The Smartrec project considers an aspect of industrial heat generation which historically has been the reason for companies to reject opportunities to recover lost heat, which is cyclic heat sources. When smaller companies or batch producing companies have a heat source which is not continual, the ability to recover heat and use it for what are generally constant heat load requirements, the feasibility of heat recovery and its use, diminish in viability.



FIGURE 2: Typical Aluminium Furnace Cycle

Therefore, the ability to successfully store the heat energy and use it in between the heat source peaks give the industrial end user a feasible method of recovering heat from their process. These such challenges are present within the Aluminium recycling industry where the re-melting of scrap Aluminium materials is a batch process, therefore the heat source from the furnace is cyclic and the options for the successful use of the heat energy are continuous.

The options for use of the energy in the Aluminium Industry are:

- a) Pre-heating of the furnace burner air to increase efficiency of the furnace and bring down cycle times.
- b) Pre-heating of scrap materials prior to entry to the furnace which also increases the melting efficiency of the furnace.
- c) Electricity Generation via steam using ORC (Organic Rankine Cycle).
- d) Space Heating for office blocks etc.
- e) Water heating for offices or local communities

In order to design and size the Smartrec system for a specific application it is necessary to acquire the specification of the waste heat (heat source). Potential Smartrec customers must provide detailed information of their equipment and processes.

Quantity	UM	Value
Description of the heat		
source		
No. Of cycle per day	n.	_
Cycle duration	Н	
Waste heat per cycle	kJ	—
Cycle duration (heat	h	—
transfer)		—
Gas mass flow	kg/s	
Gas Temperature MIN	°C	—
Gas Temperature MAX	°C	—
Gas Temperature Average	°C	—
Gas dew temperature	°C	—
Gas composition CO, CO_2 ,		_
H_2O , NO_x , SO_x , O_2 , HF ,		
hydrocarbons, any other		
relevant species		

The following table collects the essential parameters needed to design Smartrec system.

TABLE 2: Heat Source

If available, a temperature chart or graph would be useful. In case of more heat sources the information must be replicated. A general lay-out of the plant is necessary for a first verification of site location, connections, access, logistics and other matters. Gas composition and max temperature will affect the choice of HR construction material together with the inner fluid of the heat pipes. The HTF will also be selected on the basis of maximum/minimum temperature and using the DMT requirements.

Heat Valorisation

The direct use of heat recovered in the industrial process needs to be identified; the following table collects the essential parameters needed to complete the design of SMARTREC system:

Quantity	UM	Value
Description of the heat		
consumer		
No. Of cycle per day	n.	_
Cycle duration	Н	
Cycle duration (heat transfer)	h	
Power required		
Temperature required	kW	
Direct use/secondary HTF	°C	
Water consumption		
Specific requirements	m ³ /h	—
Availability of the installation		—
area, presence of technical		
constraints, interferences,		
prescriptions		

TABLE 3: Heat Valorisation

In case of direct use of HR the reduction of OPEX will determine the convenience of SMARTREC installation. It is possible that an industry will not need to transfer the recovered heat to another section of the plant (direct use of heat recovered); in this case the recovered heat can be utilized to produce electric power by a Rankine Cycle or by an Organic Rankine Cycle. The characteristics of SMARTREC system (HR at high temperature) will limit the need to use ORC making the use of traditional RC with higher efficiency preferable.

The indirect use of the heat recovered by electric power generation always produces an income that is proportional to the energy generated; the Smartrec Business Plan will consider in this case the additional revenues from power generation.

CANDIDATE HTF SELECTION AND MSTP

The Smartrec project requires the selection of molten salts as heat transfer fluids (HTFs), for use in heat exchangers operating across a wide temperature range. Molten salts have been used as HTFs in various applications (e.g. the nuclear power industry and the concentrated solar power industry) for a considerable time; however, the specific demands of the Smartrec project require a wider thermal operating window than can be achieved using the majority of molten salt based HTFs available commercially.

The aim of the described study therefore was to identify one or more candidate molten salts capable of meeting the consortium's specified criteria for adoption as a heat transfer fluid (HTF) within the Smartrec project, through the use of the SOLFIT screening program and a literature review of molten salt corrosion of typical engineering alloys.

SOLFIT, a proprietary third party multi-component platform used by with permission by TWI Ltd in the project, consists of several integrated software suites, intended to facilitate the interrogation of a central database of material properties in terms of a number (up to 40) of technical variables [4]. These variables include physicochemical, environmental/toxicological, engineering and economic factors relevant to material selection. As per standard practice, user requirements were identified and established in discussion with relevant consortium partners and collated using a template questionnaire. This questionnaire was then employed as the basis for the codification of the user requirements into numerical values suitable for use as SOLFIT input variables.

Ideally, a heat transfer fluid shall have the following properties:

- Compatible with construction materials and DMT filler material
- Not violently reactive with air or water
- Low cost
- Good heat transfer properties
- Molten and stable in suitable temperature range
- Easy to clean/process and clear up in case of a leaky pipe.

Based on the above requirements, an additional literature review of several candidate molten salts was carried out, in order to investigate the best heat transfer fluid. These are broadly divided into categories based on their counterpart anions.

The use of molten salts as heat transfer fluids and/or thermal storage media is established within a number of industries as such, several such materials are commercially available; however, within the Smartrec project, it was necessary to determine:

a.) whether any of the established commercial materials (single component or eutectic mixtures) possessed the requisite combination of properties to be suitable for use under the intended operational conditions[5][6][7];

b.) if this proved not to be the case, whether one or more appropriate material(s) could be identified or formulated from a wider assessment of the range of salts and eutectic blends available in general.

The determination of the aforementioned two factors was undertaken within the framework of the SOLFIT system used by TWI Ltd. for the purposes of the screening of solvents, ionic liquids and molten salts against user-specified criteria.

While the next generation of Smartrec systems will have a broad base of heat transfer fluids to choose from, the current technology is restricted by engineering alloys used in available components for handling molten salts. DMT and HPHE construction from a wide variety of engineering alloys is viable in theory, current suppliers of valves and pumps for molten salts or high temperature liquids are only available from a relatively small number of suppliers.

The materials of construction are typically 304 or 316 stainless steels. As such, it is necessary to select salts and purification conditions that will be compatible with these currently available pump materials. Salts with superior thermal properties (but possibly greater corrosion issues) may be considered for the next generation of Smartrec.

Molten Salt Test Plant (MSTP)

A Molten Salt Test Lab Plant (MSTP) has been designed and assembled to test the different molten salts under real operational conditions and therefore understand critical issues and technological problems before moving to full demonstration scale. The design of the MSTP has been developed considering the possibility to test different kind of Molten Salts therefore to be suitable to the max extension of data ranges.

A first request from the consortium was to evaluate the possibility to test HTF up to 630°C therefore the analysis of potential HTF was reduced to MS and Liquid Metals (LM). Both MS and LM are usually utilized as HTF at ambient pressure therefore the design of MSTP has proceeded with this assumption. The design started with the layout definition; the preliminary dimensioning of the components was made taking as a reference the characteristics of FLiBe and HITEC because their physical characteristics comprehend a wide range of potential HTF to be tested in the system.

The possibility to test LM (such as Na or NaK) in the MSTP was discarded because of safety and economic reasons. The design of MSTP has been developed to make use of commercial components as much as possible; nevertheless, some customized components were necessary.

The material selection of the MSTP system was initially evaluated under a wide range of material: steel/alloy as SS304, SS316, SS347, Hastelloy B and N, Incoloy 800H, Hayness 556, HR-160. Ceramic coatings were also evaluated to limit corrosion effect at high temperature but their brittle nature made them unsuitable for the MSTP application. The high temperature corrosion resistant material mentioned above have very high purchasing and manufacturing costs leaving as a realistic selection only SS304 and SS316.







(b)

FIGURE 3: TT I-6 Mounting details (a); E-7 and auxiliaries details (b)

The MSTP has been tested with Nitrate salts NaNO₃-KNO₃ (65%-35%). The solar salts are currently utilized in industrial plants especially in the CSP Plants and their characteristics and performances are well known. In industrial HR applications it may be necessary different or improved thermochemical HTF characteristics because of higher temperature or higher heat storage capacity; at the same time an industrial application requires a fast break even point and a positive Business Plan. The utilization of fluoride and chloride HTFs for instance would allow higher performances in term of heat recovery (higher thermal conductivity and heat capacity) but would generate concerns on plant materials in contact with them. They would require expensive alloy for plant components like the cited SS347, Hastelloy B and N, Incoloy 800H, Hayness 556, HR-160 determining most probably a non-profitable investment in the HR initiative because of the high cost of material (material and manufacturing costs). The availability of the MSTP allows testing of other HTFs under simulated operational conditions and determines their effects on the most common materials used in industrial plants like SS304 and SS316. It is also possible to test fluorides, chlorides or other highly corrosive HTFs taking into account that the performances of main components, particularly the HTF pump, will decrease proportionally of the test duration time.





(a)

FIGURE 4: MTSP General View (a); MSTP Test Section (b)

SMARTREC SYSTEM SIMULATOR

The finite element multi-physics software FlowPhys has been extended by a newly developed module capable of simulating time-dependent non-linear flow and heat transfer of compressible molten salts in pipe networks. This solver has been used to create a numerical model of the Smartrec system to guide design of piping system and insulations, as well as to guide control strategies. The solver includes material models for HITEC salt as well as models for the Dual Media Thermocline (DMT) thermal storage and the Heat Pipe Heat Exchanger.

To enable simulation over long time periods, i.e. days, the time-stepping is implicit with equilibrium iterations for each time step which allows for large time steps. The mass and momentum equations are solved coupled, while the energy equation is solved sequentially but still within the equilibrium iteration loop. The equilibrium iterations are non-linear and are solved with the Newton-Raphson method in each time step. Usually the solution converges in just a few iterations. The solver also takes into account mass, heat flux, pressure, and temperature for the pipe network joints. Heat transfer between the fluid inside the pipe, pipe wall, insulation layer, and ambient environment is also included in the formulation. The software is of general character and can in principle analyse any pipe network.

The HITEC salt fluid properties are calculated from the semi-empirical models presented in [8], [9], [10]:

$\rho = 2080 - 0.733 * (T - 273.15)$	$\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$	415 < T[K] < 808
$\mu = \frac{e^b + e^{-b}}{e^b - e^{-b}} - 0.999, b = \frac{5.9(T - 9.638)}{990.362}$	[Pa s]	415 < T[K] < 808
$C_P = 1560 - (T - 273.15)$	$\left[\frac{J}{kg K}\right]$	415 < T[K] < 808
$k = 0.78 - 1.25 \times 10^{-3}T + 1.6 \times 10^{-6}T^2$	$\left[\frac{W}{m K}\right]$	415 < T[K] < 808
$c_{HITEC} = 2040 - 1.323(T - 415)$	$\left[\frac{m}{s}\right]$	450 < T[K] < 693

Several time-dependent 1D models for the pressure losses and temperature profiles in the DMT have been developed and implemented into the simulator. The temperature distribution model takes into account heat transfer between the fluid, DMT walls, and DMT filling (stones and sand), while the pressure loss distribution model takes into account flow velocities, DMT dimensions, flow regimes (laminar / turbulent), and whether the filling stones are smooth or rough. For molten salt loop calculations, the HPHE has been implemented as a heat source term with a given power rating. Notice that this simplification excludes the thermal mass of the heat exchanger, leading to faster up/down ramping of power than what is physically possible. Pressure loss models of the HPHE have been developed based on HPHE geometry, dimensions, flow velocities and flow regimes.

Heat transfer to/from fluid, pipe wall, insulation, and environment is modelled by:

$$q_r = \frac{T_{Fluid} - T_{Ambient}}{\frac{1}{2\pi r_1 L h_1} + \frac{ln\frac{r_2}{r_1}}{2k_A \pi L} + \frac{ln\frac{r_3}{r_2}}{2k_B \pi L} + \frac{1}{2\pi r_3 L h_3}}$$

Then to the environment is

where the heat transfer coefficient to the environment

$$h_3 = 8 + 0.04(T_{Ambient} - T_3)$$

and the heat transfer coefficient between the fluid and inner wall is modelled from

$$h_1 = \frac{Nu * k_F}{D_1}$$

where the Nusselt number is approximated by Nu=3.66 for laminar flows and calculated from the Gnielinski correlation for turbulent flows

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7(Pr^{\frac{2}{3}} - 1)\sqrt{f/8}}$$

To analyze the dynamics and control of the system, PID controllers have been implemented into the simulator. Assuming an intermittent heat input cycle with the burner on / off such that the HPHE can deliver 200kW of heat to the system for 6 hours, then decreases to 10kW for another 6 hours, and with the simplification that the thermal mass of the HPHE is not included in the modelling, the heat input will have a cycle as shown by the green line in Fig.5a. In the same figure, the system is controlled such that the temperature right after the end user heat extraction (purple line) will be constant. Thus, the end-user temperature is kept at the constant level by controlling heat power extraction. An example of another control strategy is shown in Fig.5b, where the cycle period is shorter, 8 hours, and where the controller aims to keep the end-user heat power extraction at a constant value while the end-user temperature is allowed to vary. With this control strategy, it is seen that the heat power extraction is reaching a constant value over the whole cycle after 16 hours.



FIGURE 5: Example of Smartrec system end-user heat extraction: with constant end-user temperature(a); with constant enduser heat power(b)

CONCLUSIONS

The Smartec project has been designed through a multidisciplinary approach; partners with different specific skills have collaborated to implement a valuable solution for heat recovery in industrial applications. The main Smartrec objectives – high temperature and switch from batch to continuous heat recovery- have been reached by the application of latest technologies on Heat Transfer Fluid, Heat Storage and Heat Exchanger design and manufacturing. Major constraints in Heat Recovery in industrial processes like low temperature and non-continuous availability have been assessed by a standardized solution tested and operated in real applications.

In the future development, Smartrec System would hopefully benefit from higher performance materials (compared to SS304, SS316) like SS347, Hastelloy B and N, Incoloy 800H, Hayness 556, HR-160 etc., that were

not utilized at the moment because of high purchasing and manufacturing costs. In this case, the utilization of fluoride and chloride HTFs for would allow higher performances in term of heat recovery (higher thermal conductivity and heat capacity).

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http://smartrec.eu/



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