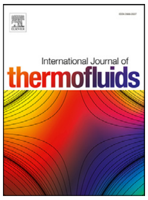
International Journal of Thermofluids 1–2 (2020) 100002

Contents lists available at ScienceDirect

International Journal of Thermofluids

journal homepage: www.elsevier.com/locate/ijtf



ETEKINA: Analysis of the potential for waste heat recovery in three sectors: Aluminium low pressure die casting, steel sector and ceramic tiles manufacturing sector

Bakartxo Egilegor[a,*], Hussam Jouhara[b], Josu Zuazua[c], Fouad Al-Mansour[d], Kristijan Plesnik[e], Luca Montorsi[f], Luca Manzini[g]

[a] Ikerlan, Technology Research Centre, 20500 Arrasate-Mondragón, Spain
[b] College of Engineering, Design and Physical Sciences, Institute of Energy Futures, Brunel University London, Uxbridge, UB8 3PH, UK
[c] Fagor Ederlan, 20500 Arrasate-Mondragón, Spain
[d] Energy Efficiency Centre, Josef Stefan Institute, 1000 Ljubljana, Slovenia
[e] Metal Ravne Sij, 2390 Ravne na Koroškem, Slovenia
[f] University of Modena and Reggio Emilia, Reggio Emilia, Italy
[g] Atlas Concorde S.P.A., 41042 Fiorano Modenese MO, Italy

ARTICLE INFO

Article History:
Received 19 July 2019
Revised 2 October 2019
Accepted 14 October 2019
Available online 23 October 2019

Keywords:
Energy efficiency
Waste heat recovery
Heat pipe
Heat exchanger

ABSTRACT

In the framework of the ETEKINA project, waste energy streams have been analysed at an aluminium automotive parts production facility in Spain, at a steel foundry in Slovenia and at a ceramic tile production unit in Italy. The aim is to recover more than 40% of the waste heat contained in the exhaust streams and reuse it within the industrial plant rather than emitting it to the atmosphere. To select the applications where the profitability of heat recovery can be demonstrated, the flow rates and temperatures of the applicable exhaust streams have been measured and analysed to select the processes for waste heat recovery and it's re-used in the three industrial plants. The demonstration of the cost-effective waste heat recovery is to be made by using heat pipe heat exchangers (HPHEs) and the processes whereby the heat recovery installations will be erected have already been selected. HPHEs were selected as a heat recovery technology due to their advantages and key features over convectional heat exchangers considering space restrictions, pressure drop limitations, and other waste stream challenges. The challenges include high temperature of the waste and the heat sink streams, fluctuations in the waste stream flow rate and temperature, presence of corrosive moisture such as sulphuric acid in the waste stream, and the presence of particles in the waste stream which can cause fouling leading to failure of convectional technologies. Furthermore, HPHEs are maintenance-free and can have payback period of less than three years.

1. Introduction

Currently, greenhouse gas emissions and energy dependence still pose a risk to the European economy and lifestyle. In 2015, the gross inland consumption of energy in the European Union reached around 1627.5 Mtoe with a dependency rate at 54% [1]. Therefore, the EU is looking for a clean, sustainable, decarbonised and competitive energy system [2]. In order to preserve the environment and to promote sustainable consumption and production, the European Council set three key targets for 2030: a 40% cut in greenhouse gas emissions (from 1990 levels), a 27% share for renewable energy (in comparison with 2005 levels) and a 32.5% improvement in Energy Efficiency (in comparison with 2005 levels) [3].

Energy Efficiency is one of the most important pillars of a sustainable energy policy and a key component of climate change mitigation strategies. Energy Efficiency is a key factor to ensure a safe, reliable, affordable and sustainable energy system for the future. As well as to boost industrial competitiveness, create jobs, reduce energy bills, help tackle energy poverty and improve air quality. The main sectors of energy consumption in the EU are: transport, electricity generation and the industrial sector, which in Europe accounts for 35% of total energy consumption [4]. Success in this aspect will depend largely on

---

Nomenclature/Keywords: HPHE, heat pipe heat exchanger; FHP, Flat Heat Pipe; SPP, Simple Payback Period; EII, Energy -intensive industries; SP, sub process; WH, waste heat; HS, heat sink; SBC, steam bottoming cycle; ORC, organic rankline cycle; CHP, combined heat and power; HTP, heat treatment process; QT, quenching treatment; SHT, Solution Heat Treatment; SHTF, solution heat treatment furnace; AHT, Ageing Heat Treatment; AHTF, ageing heat treatment furnace

*Corresponding author.

E-mail address: begilegor@ikerlan.es (B. Egilegor).

https://doi.org/10.1016/j.ijft.2019.100002

industrial energy efficiency, particularly on the energy efficiency of energy-intensive industries (EII) which may account for 80% of the total industrial energy consumption [5]. The industrial sectors covered by ETEKINA research project present high technical potential for reducing energy consumption (22%, 24% and 19% for non-ferrous-metal, iron-and-steel and non-metallic-minerals, respectively) with the current technology status [5]. Although the opportunities for high energy savings exist, these measures are not currently being introduced in practice, as indicated by the energy efficiency gap theory [6]. These measures would not only involve a reduction in energy consumption, but also a reduction in production costs and a cut in Greenhouse Gas emissions, which returns benefits to society [7]. In any case, the current trends in energy policy and in global energy consumption may result in higher energy prices and, therefore, in a further increase in the need for industrial energy efficiency [8]. The overall objective of the ETEKINA project is to improve the energy performance of industrial processes. For this to be possible, the valorisation of waste heat by a turnkey modular heat pipe-based heat exchanger (HPHE) technology adaptable to different industry sectors will be addressed within the project. It will be demonstrated in three industrial processes from the non-ferrous, steel and ceramic sectors in order to demonstrate the economical feasibility and effectively the market potential of this solution.

The HPHE are recognized as one of the most efficient passive heat transfer technologies.

Waste heat recovery system for industrial processes have recently attracted considerable interest due to the raising awareness of the affects of global warming and the constant increase of fuel prices. Therefore, the use of the waste heat recovery from industrial exhaust streams plays an important role for reducing the overall energy consumption of industrial sites.

Numerous technologies for improving the performance of industrial processes in terms of energy consumption already exist and a comprehensive review has been provided by Jouhara et al. [9].

Jouhara et al. [9] identified different strategies and methods for the waste heat recovery such as regenerative and recuperative burners, economisers, waste heat boilers, air pre-heaters, recuperators, regenerators, plate heat exchangers, heat pipe systems, heat recovery steam generator and thermodynamic cycles; this study evaluated the advantages and disadvantages of each system and technique. [9]

Wolley and Luob [10] presented a framework to provide manufacturers with a methodology in assessing waste heat source potential and the appropriate heat recovery technology as well as the economic benefit that the technology can bring [10].

Three different unconventional technologies to convert the waste heat into power such as the air turbine cycles which referred as air bottoming cycle, carbon-dioxide based power cycle (transcritical and supercritical CO_2) and Kalina bottoming cycle are presented in an extensive review in [11]. The authors discussed these technologies against convectional bottoming cycles such as steam bottoming cycle (SBC) and organic Rankine cycle (ORC).

In the literature, the use of heat recovery systems has been investigated and applied in different sectors such as steel, food, paper, ceramic [9].

In this regard, the ceramic industry sector is considered as a-high intensive energy sector. According to Confindustria Ceramica report [12], the Italian ceramic tile and refractory materials sector is characterized by a consumption of gas methane equal to 1.5 billion cubic meter per year and by an electricity demand of 1800 GWh/y.

Thus, due to the high level of waste heat that is lost within the ceramic industry it is considered to be suitable for the recovery of industrial waste heat with the aim of reducing the gas greenhouse emission, cost of energy used and overall improving the energy efficiency of the process.

The ("Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry", 2007) [13] presented a review on several measures and techniques that can be applied in order to enhance the industrial process performance. One of the principal waste heat recovery practice mentioned in [13] is the recovery from the excess heat of the kiln. The heat can be recovered from the cooling zones of the roller kilns to heat up the air required by the drying phase or used through the mean of other methods such as CHP or ORC to generate heat and electricity for the plant [9].

The employment of cogeneration units is convenient due to the simultaneous demand of heat and electric power required by the ceramic process.

Mezquita et al. [14] presented a theoretical methodology for quantifying the savings due to the energy recovery of the cooling gases in the exhaust chamber; in the test case analysed has been quantified a saving up to 17%.

In [15] an organic Rankine cycle has been proven an efficient way to recover heat in the indirect cooling air of a ceramic furnace in order to produce electricity. This study demonstrated that the thermal power recovered from the clean exhaust ranged from 128.19 kW to 179.87 kW while the maximum electrical power output ranged between 21 kW and 18.51 kW.

Beltran [16] proposed a cogeneration system for the ceramic industry where the heat generated by the cogeneration plant is injected into a mixing chamber with the hot air coming from the cooling section of the kiln. If the temperature is not high enough, a gas burner is used.

In the same way as in the case of the ceramic manufacturing industry, the EU commission has proposed a review of Best Available Techniques (2005–2017) for the non- ferrous metal sector, which covers foundries, smitheries and pressure die casting manufacturing process [17,18]. Indeed, the heat recovery system technologies are included among the measures proposed by the European Commission.

In this regard, Enderle et al. [19] proposed a wide analysis of energy savings by means of combining the process water reuse and heat recovery technologies for an aluminium high pressure die-casting factory. The analysis is focused on melting/holding furnaces and on water management used in die casting cooling and mechanised components cleaning.

The recovery of waste heat by heat exchangers and distribution either to other parts of the steelworks or to a district heating network has been proposed as one of the best available technologies [20] to improve energy efficiency in steel processing sector.

2. Process descriptions and waste stream characteristics

The processes described below belong to the energy-intensive industry (EII) sector and they are characterized by very high energy production costs as well as by an important level of CO_2 emissions. Energy production costs effectively account for up to 40% of total production costs in some EIIs. At the same time, almost all the energy used is finally rejected to the atmosphere as waste heat, which may be recovered or re-used.

2.1. Aluminium low-pressure die-casting plant

The first case study is focused on an Aluminium Die Casting industry which produces low weight metal parts with high mechanical properties. The aluminium alloy is generated and melted in a furnace. After that, the liquid aluminium alloy is degassed and transported to the die-casting section. The liquid alloy is introduced into the die-casting device, where parts are formed and cooled. Then the solid parts are placed in baskets and subjected to a Thermal Heat Treatment Process (HTP), at different levels of temperatures and times, in order to improve the mechanical characteristics of the parts. Finally, the parts are transported and they pass several quality controls. The HTP (represented in Fig. 1) is the second major consumer of thermal

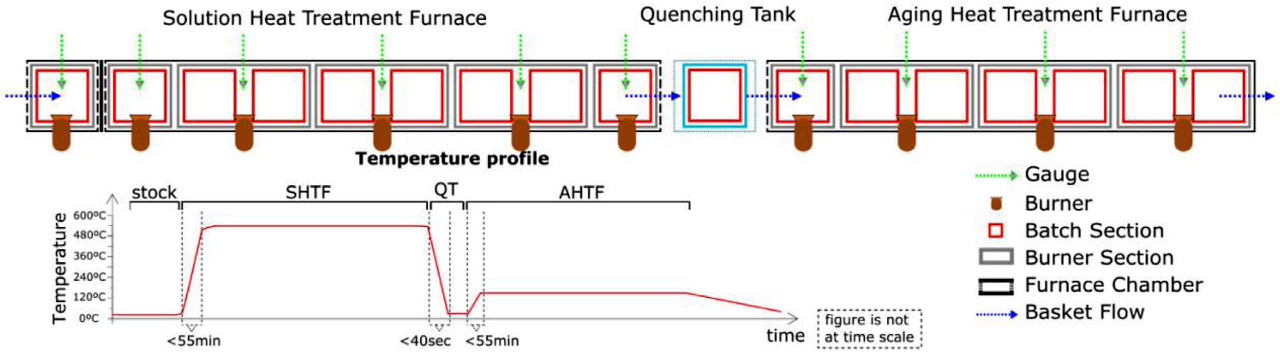


Fig. 1. Heat treatment process.

energy (from natural gas) of the plant, following closely behind that of the melting furnace. Besides, Solution Heat Treatment (SHT) subprocess presents a higher temperature waste heat than melting subprocess waste heat (>400 °C versus 170 °C).

The HTP consists of three sub-processes: a solution heat treatment furnace (SHTF), a quenching tank and an aging heat treatment furnace (AHTF), which operate on a push strategy. The parts are placed into steel baskets, optimizing the space to the geometry of the parts. The AHTF consumes around 15% of the total HTP energy consumption.

Exhaust waste heat streams are still discharged to the environment. These streams are summarized in the following table (the numbers in the last column show the percentage of the heat discharged in the environment in each sub-process with regard to the total heat discharged to the environment):

Sub-process (SP)	WH source	SP WH vs. total WH
Melting furnace	Fumes at 170 °C rejected to the atmosphere.	18% (single stream)
Casting	Water at 40 °C dissipated in a cooling tower.	22% (7 streams)
Parts cooling	Water at 40 °C dissipated in a cooling tower.	9% (7 streams)
Solution treatment	Fumes at >400 °C rejected to the atmosphere.	26% (2 streams)
Quenching treatment	Water at 40 °C dissipated in a cooling tower.	20% (2 streams)
Ageing treatment	Fumes at 135 °C rejected to the atmosphere.	5% (2 streams)

The exhaust gases from the melting furnace are the ones with the highest energy content from a single waste heat stream. However, the moderate temperature, the critical process location and significance, as well as the limited replicability[1] reduce the interest in it. The second highest waste heat streams within the process are from the exhaust gases from the SF, each of them accounting for almost 15% of the total heat rejected. For these streams, temperature levels are estimated to be between 520 °C and 540 °C in the source which is an interesting level to consider for potential recovery (260 kW per stream) and re-use as will be explained in the next point. The SF waste heat source has low variation during the working period (except from initialization and switch-off). The waste stream presents low levels of corrosiveness due to its composition: natural gas combustion fumes with high excess air. The nominal mass flow rate is around 1580 kg/h.

The rest of the waste heat coming from the process, although considerable for some of the streams, is either too diffuse (above 20% distributed among 7 casting machines) or at too low temperatures (below 80 °C in the quenching heat treatment) for practical recovery and re-use.

2.2. Steel plant

The second case study is focused on a steel plant, for which the more representative sections are the Steel Plant, where steel is generated, the Forging Shop, where billets, rod or other surfaces are obtained, the Rolling Mill, where the previous products are machined and treated, and a wide range of heat treatment and machining processes for the final treatment of special steels.

The main process of interest is related to the additional utilisation of waste heat from the heating furnaces (process of heat treatment). The selection of the billet-heating furnace (Allino) was made on the assumption that this technology has the highest replicability potential in the steel processing company. The selected process heats steel billets in a natural gas-fed furnace. The conditions inside the furnace are very restrictive and a complex air introduction system to regulate the pressure is implemented. The furnace consists of several gas burners distributed along the furnace in 4 heating zones and an integrated recuperator (heat exchanger) partially increases the combustion air temperature. As a source for the excess heat extraction from flue gases a heat stream after the recuperator has been selected, as presented in Fig. 2.

The main challenge related to the use of selected heat stream is its high variability. For the selected heat stream, temperature levels are between 200 °C and 450 °C with peaks over than 500 °C. Hence, the average value amounts to 360 °C. The mass flow rate of the flue gas varies between 1000 kg/h and 8000 kg/h, which represents the main design challenge. On the other hand, the potential heat recovery may reach high values (up to 620 kW). The excess heat stream presents low levels of corrosivity due to its composition: natural combustion fumes with excess air.

2.3. Tile manufacturing plant

The third case study is focused on a ceramic tile manufacturing plant. The process starts by selecting the raw materials and, after a first mixing of the basic components, milling them in continuous mills with a mixture of water. A first water removal is carried out by spray drying. Then, forming takes place, by mechanically compressing the paste in the die. After forming, the tile body is dried again to appropriate levels for firing. Once tiles are decorated they can be fired. Firing is one of the most important tile manufacturing process stages as most tile characteristics depend on it. To manufacture unglazed dry pressed tiles the temperature in the kilns is about 1250 °C.

Firing is mainly carried out in single-deck roller kilns, where the tiles travel over rollers and the heat required for firing is provided by

---

[1] In the rest of the plants of the manufacturer the melting process is made using furnaces with another technology.

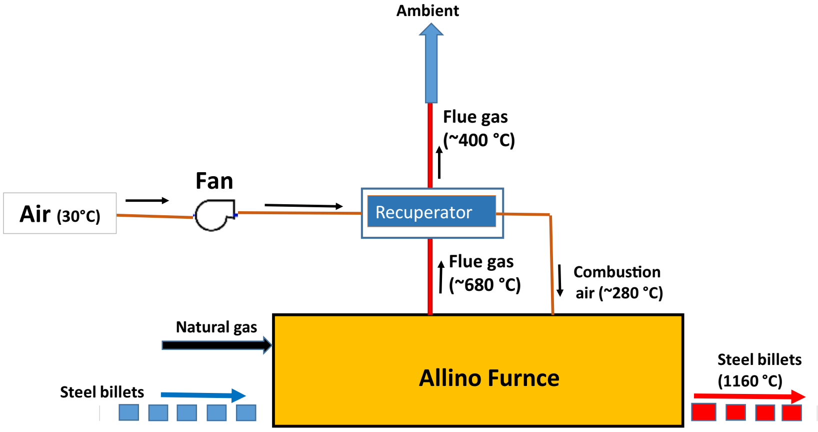


Fig. 2. Schematic representation of the billet heating furnace in steel processing industry.

natural gas–air burners. An important characteristic of this type of kilns are the internal flows which are in counter-current with respect to the movement of the tiles; the chimney placed at the entrance of the kiln, see Fig. 3(b), keeps a pressure lower than the one inside the chambers, which causes a movement of cold air from the rapid cooling zone. The return of air to the inlet area of the kiln is used to transfer thermal energy from the firing zone to the incoming material, thus performing a pre-heating phase without installing burners in the first modules of the kiln. The gases from the firing and the pre-heating zone are exhausted via the stack placed at the inlet at a temperature of approximately 250 °C; most of the cold air introduced into the cooling zone exits through one/two chimneys located in the end zone of the system. The ceramic tile manufacturing process ends with sorting and packing.

Energy sources used in the ceramic process are natural gas and electricity, with roughly 80% of the energy consumption credited to gas. Firing is responsible for 53% of the thermal consumption, followed by spray drying (35%) and drying (10%). Several heat streams are discharged to the environment, as summarised in the following table:

Sub-process (SP)	WH source	SP WH vs. total WH
Spray dryer	High-wet air at 100 °C rejected to the atmosphere.	50%
Dryer	Low-wet air at 130 °C rejected to the atmosphere.	12%
Kiln - exhaust gases	Fumes at 250 °C rejected to the atmosphere.	21%
Kiln - cooling	Air at 70 °C rejected to the atmosphere.	17%

Both dryer and spray dryer waste heat sources are of low temperatures and relative high vapour water content, and the kiln cooling source has already been used, reducing the final temperature to 70 °C. On the other hand, exhaust gases from the kiln have the highest energy content in the plant. This stream has interesting temperature levels and flow rate (220 °C–250 °C, 10,000–15,000 Nm^3/h per kiln), potentially recovering 300–500 kW/kiln of thermal power. However, the kiln exhaust gases contain dust and pollutants which prove to be very aggressive to metal.

3. HPHE technology

Waste heat can be effectively and efficiently be recovered with the use of Heat Pipe Heat Exchanger (HPHE) technology [21]. A heat pipe is an equipment that uses two phase heat transfer phenomena to transfer waste heat from one location to another. As can be seen from Fig. 4, a heat pipe consists of a vacuumed sealed container which may include a wick structure and an amount of working fluid such as acetone, water, ammonia methanol or sodium [22]. When heat is applied from a heat source to one end of the heat pipe, the working fluid boils at this end (which is called an evaporator) where it is in equilibrium with its own vapour, and flows from the evaporator via the adiabatic section to the other end (condenser). The working fluid vapour rejects the latent heat at the condenser to a heat sink leading to condensing the vapour to liquid. The condensate flows back to the evaporator section by flowing through the wick structure which provides a capillary action in wicked heat pipes. In wickless heat pipes which are also called thermosyphons, the liquid flows back by the assistance of gravity [22]. When the liquid working fluid reaches the evaporator section, it evaporates and the two-phase cycle is repeated.

Several different studies have been conducted to employ the heat pipe technology to recover waste heat from industrial applications. Jouhara et al. [23] designed a novel flat heat pipe (FHP) based heat exchanger that can be used to recover waste heat from a production line of steel wires by radiation. As shown in Fig. 5, the flat heat pipe heat exchanger consisted of several heat parallel pipes connected through a bottom collector and a top header. The FHP was examined experimentally at the hottest point of the cooling zone of the production line. The FHP was cooled by a water flow as heat sink to absorb the recovered waste heat from the condenser. In conclusion, it was observed that highly efficient heat recovery of the order up to 17 kW. The FHP heat recovery represents 4.5% of ETEKINA's HPHE's duty considering it is 380 kW as an average of the three sectors heat recovery targets. It was highlighted that the heat recovery capacity can be further increased by utilising multiple modular FHPs to achieve up to 250 kW of waste heat recovery.

Delpech et al. [24] investigated experimentally a heat pipe heat exchanger to recover waste heat from ceramics kiln. As can be seen from Fig. 6, in this study the HPHE was designed by incorporating several parallel tubes which can be placed on top of hot ceramic tiles that go through cooling process. The heat pipe system recovered the heat by absorbing the heat from the kiln and transporting it to a water flow in the condenser. The experimental results indicated the waste heat recovery of up to 4 kW can be obtained through this system. Though this study, the use of heat pipe technology for waste heat recovery in industrial applications was shown and proven to be a highly efficient method of waste heat recovery. This lab-scale heat pipe represents 1% of the average ETEKINA's heat recovery target.

Moreover, in another study, Delpech et al. [25] discussed the application and performance of a heat-pipe based heat exchanger to recover waste heat and improve the overall energy efficiency of the ceramic production industrial processes. Whereby, a counter flow heat exchanger as shown in Fig. 7 was designed to be installed and

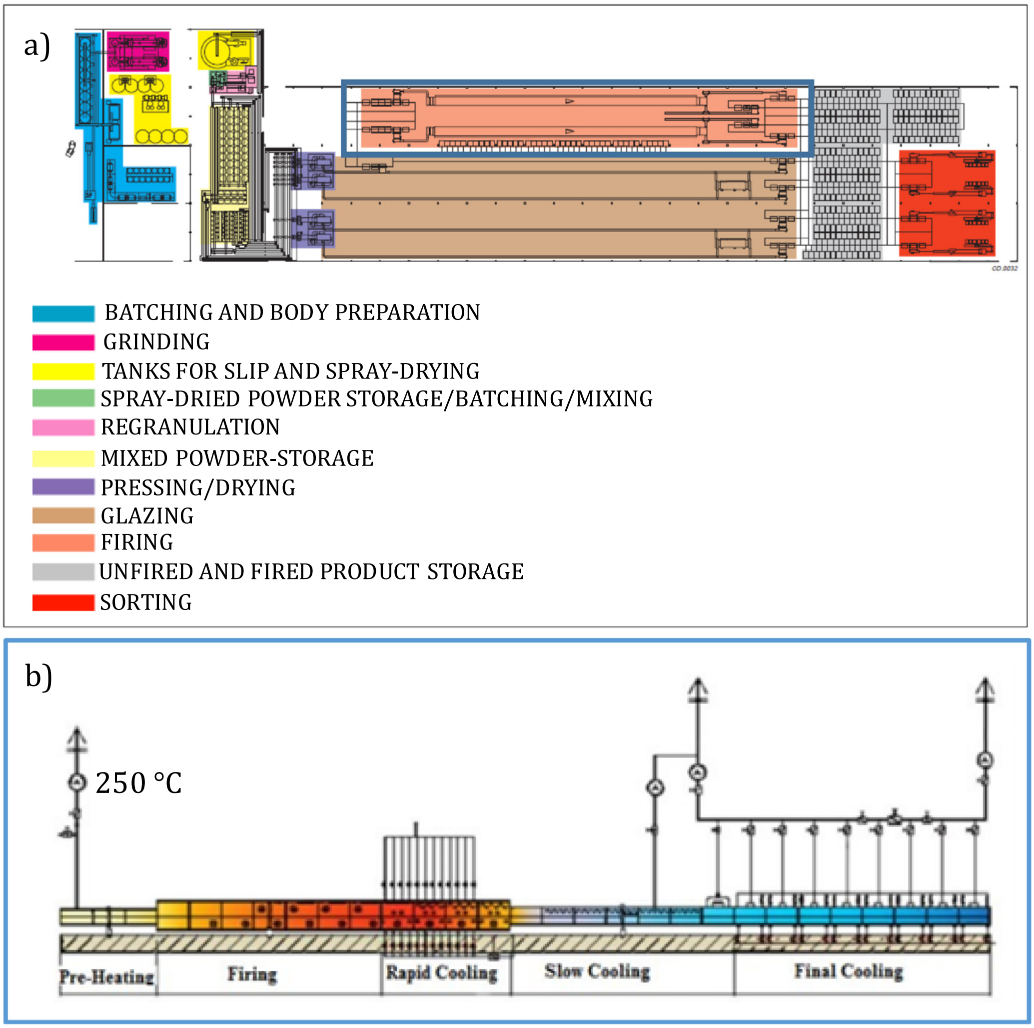


Fig. 3. Successive stages of the ceramic tile manufacturing process (a) and main sections of the ceramic kiln-firing process (b).

recover 100 kW of waste heat from the cooling stack of a ceramic kiln and deliver it to the pre-kiln dryer. In this regard and through a combined theoretical and numerical approach the usability of the technology was investigated, and it was concluded that more than 863 MWh/year of thermal energy can be recovered from the ceramic kiln. This meant that yearly the use of nearly 110,600 Sm^3 of natural gas can be retained while the production of almost 164 tons of CO2 can be reduced per year. The heat recovery duty of this industrial HPHE represents 26% of the average heat recovery target of ETEKINA HPHEs.

Ma et al. [26]. investigated experimentally a heat pipe heat exchanger for waste heat recovery in the steel industry. The HPHE recovers the heat from a waste water stream to a clean water flow. The effectiveness and exergy efficiency were studied and the optimum water flow rate corresponding to the highest effectiveness and exergy efficiency was determined. The HPHE system recovered up to

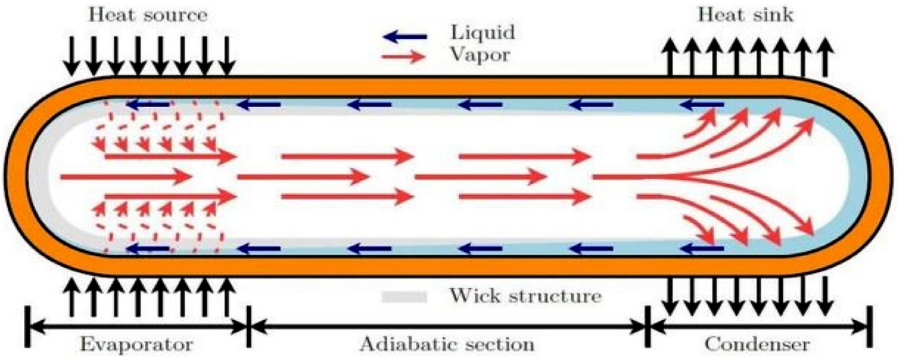


Fig. 4. Schematic of a heat pipe [29].

Fig. 5. Heat pipe heat exchanger used in the steel industry [23].

7.3 kW which represents 1% of the average of ETEKINA's industries heat recovery target.

Having noted that it is investigated, as different industrial processes consume and produce different amount of energy, therefore, it is important to look into what processes are used and analyse what quantity of waste heat is produced. Based on this, a specific design of a waste heat recovery technology can be adopted to improve the overall efficiency of a system. Nevertheless, in a comprehensive review conducted by Jouhara et al. [9] and it was summarised that the use of heat pipe based heat exchanger technologies are very ideal and exemplary for waste heat recovery. This is indicated to be mainly due to the fact that the technology offers very high effective thermal conductivities while minimising temperature drop of heat transfer.

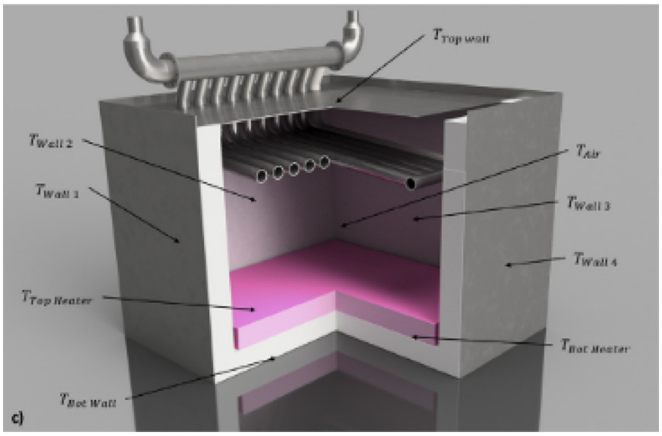


Fig. 6. Experimental design of the ceramics kiln and the heat pipe based heat exchanger [24].

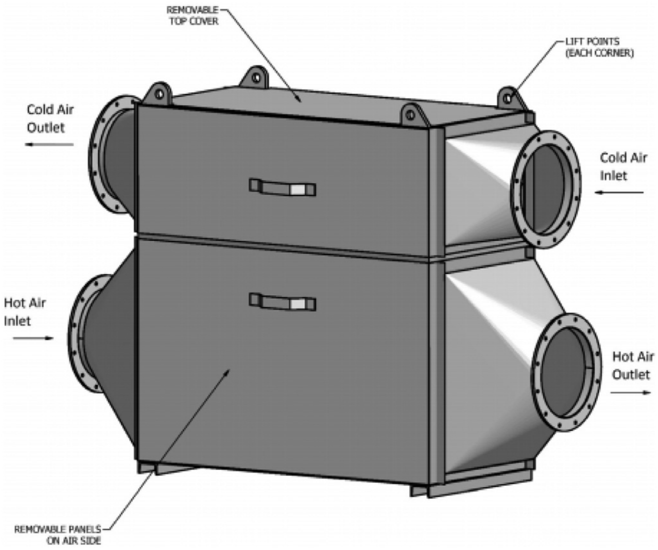


Fig. 7. Waste heat recovery counter-flow heat pipe based heat exchanger [25].

Each heat pipe is considered as a heat exchanger where the heat is transferred inside the heat pipe passively by two-phase heat transfer from the evaporator to the condenser. The heat is transferred by forced convection from the heat pipe to the exterior stream and vice versa. Whereas heat is transferred directly from the hot stream to the cold stream by forced convection and conduction heat transfer in convectional heat exchangers such as tubular recuperators and plate heat exchanger.

Thus, the heat transfer area at the heat sink side is linked directly with the heat transfer area at the heat source side with respect of the length of the tubes in convectional heat exchangers. Therefore, changing the length of the pipes in conventional heat exchangers will affect the pressure drop for both the hot and cold streams.

While the passive operation and the scalability of the heat pipe allow to have a heat transfer area at the heat source stream different from the cold stream (heat sink) by changing the length of the evaporator individually from the length of the condenser. Hence, the heat transfer coefficient and the pressure drop at the heat source can be separately designed without interfering with the stream flow at the heat sink side. As a result, these key features of heat pipe heat exchangers highlight the advantages over the conventional heat exchangers.

Nonetheless, heat pipes do not require any maintenance, and failure of few heat pipes does not considerably influence the overall performance of the heat pipe heat exchanger. In addition, the failed heat pipes can be replaced during the maintenance cycle schedule. Moreover, heat pipe heat exchangers offer the advantage of transferring the heat between two streams without the risk of any contamination or leakage from a stream to another, and they have lower operational cost due to passive functionality when compared to other types of heat exchangers.

The isothermal surface of heat pipes eliminates the chance of presence of any hot cold or cold spot, which prevents the possibility of condensation of corrosive moisture such as sulphuric and nitric acids in the hot streams and avoids contamination of heat transfer fluids due to the exposure to high temperature.

Heat pipes are capable of transferring large amount of heat through a small cross-sectional area leading to a smaller size and weight of a heat pipe heat exchanger in comparison to a convectional heat exchanger.

4. Waste heat potential re-uses and the utilisation of HPHE technology as a waste heat recovery solution

The challenge for the sectors in the case studies in ETEKINA project will be to identify the most appropriate way to reuse the waste heat from the waste heat recovery system and to design, build, test and demonstrate the corresponding heat recovery solution. Besides in-plant layout a first identification of potential waste heat reuse has already been carried out and this is explained in the next paragraphs.

4.1. Aluminium low-pressure die-casting plant

Two possible heat sinks have been identified for the demonstration case 1: Solution furnace combustion air preheating and the ageing heat treatment furnace heat reduction/substitution.

In the first one, depending on the air preheating temperatures (300–400 °C), natural gas savings of 10–15% are estimated from the present consumption in the solution heat treatment furnace. The use of the HPHE to recover the waste heat and pre-heat the combustion air will facilitate such a high temperature for the air intake through a suitable thermal and mechanical design that will result in a cost-effective heat exchanging system.

According to the second hypothesis, the thermal treatment is a combination of two heating treatments (solution and ageing) with an intermediate cooling treatment. Due to the metal structure requirements and furnace specifications the heat treatment exhaust gases come out at a temperature close to that of the furnace's working temperature, 540 °C and 160 °C for the solution and ageing heat treatment furnaces, respectively. The natural gas thermal input of this lower temperature furnace is less than the available heat from the solution furnace exhaust gases. Thus, a straightforward recovery and re-use scheme, through the use of a HPHE unit, would be to integrate the available heat from the high temperature furnace exhaust in the lower temperature one, which would result in up to 100% natural gas savings in the latter. Moreover, this approach is expected to recover more than 40% of the sensible heat from the solution heat treatment furnace exhaust stream.

The challenge of the first approach is, besides the heat recovery system itself changing the present burners with new ones capable of operating with hot combustion air is necessary with no going back possibility. The savings of this option need to be compared against the retrofitting and installation costs. On the other hand, no more than 30% recovery of the sensible heat from the exhaust stream is expected with this approach.

For the second alternative, the challenge to integrate the heat of one process into the other, while operating the furnaces at their required specifications, needs to be addressed in order to achieve the desired final mechanical properties for the parts produced. For both options, the correct selection of the heat pipes shell material and working fluids will have to be made to ensure efficient operation and prolonged life time under such high temperatures in the evaporator and the condenser sections.

4.1.1. HPHE technology application for waste heat recovery in aluminium parts heat treatment furnaces

As mentioned in previous paragraphs the common configuration for aluminium heat treatment units is made up by a sequence of three processes: an initial high temperature unit process (solution heat treatment furnace, 540 °C), followed by a cooling unit process (quenching heat treatment pool, 40 °C) and finally a low temperature unit process (artificial ageing heat treatment furnace, 160 °C). A significant amount of heat is discarded from all three unit processes. Fig. 8 shows a heat balance for the heat treatment unit, where it is observed that almost 40% of the thermal input to the process is discarded as waste heat through the solution heat treatment furnace exhaust gases. Temperature of this stream is high enough for example to be used as thermal input for the artificial ageing furnace, so that natural gas input for the later could be reduced.

ETEKINA approach aims at achieving a recovery solution by using a HPHE to exchange heat between the exhaust fumes from the high temperature furnace and a secondary stream, the latter being then introduced to the low temperature furnace providing the necessary heat for the process. By means of inserting the HPHE between those two streams, "fluidic" separation is achieved and thus no pressure interference between furnaces will happen. On the other hand, temperature of the secondary stream could easily be controlled by means of flowrate adjustment, so that the required heat conditions are achieved before introducing it to the artificial ageing furnace. Additionally, any impurities from the exhaust fumes can be removed by the fouling management feature of the HPHE, preventing them to enter the ageing furnace. Moreover, ETEKINA HPHE solution can add interesting features like multi-recovery which could allow to

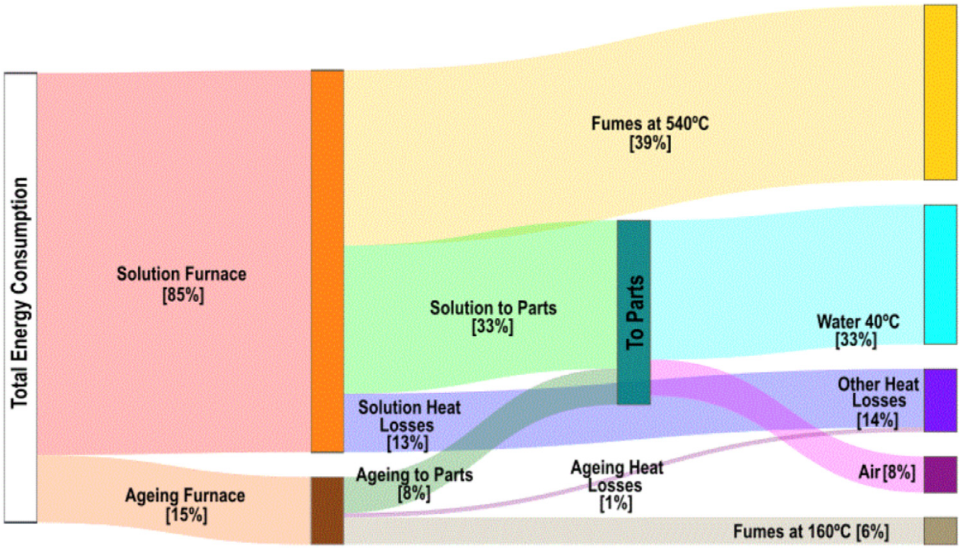


Fig. 8. Heat balance for the heat treatment unit.

simultaneously providing heat for the low temperature furnace while preheating the combustion air for the high temperature furnace. It is worth noting that this component is performing the task of particle separation, pressure/flowrate and temperature conditioning devices.

The HPHE is being designed by combining multiple heat pipes of different characteristics (working fluid and materials) to face the application that combines high temperature exhaust stream and high temperature heat sink. The selection of the heat pipe working fluid is made based on the heat pipe working temperature/ working pressure. For instance, distilled water as a heat pipe working fluid is suitable for working temperature range between 30 °C and 300 °C. While Dowtherm A is suitable for working temperature range of 150 °C–395 °C. The selection between possible working fluids candidates is made based on the physical properties such as viscosity, density, surface tension, and thermal conductivity. The shell material is selected based on the compatibility with the chosen working fluid, the operating temperature, the working fluid pressure, and the cost of the material.

4.2. Steel plant

The main interest of the steel manufacturer in the project ETEKINA is related to the additional utilisation of waste heat from the heating furnaces (process of heat treatment). Exhaust temperatures (up to 450 °C) from the stack gases of the furnaces would allow additional preheating of furnace combustion air to over 100 °C which will lead to an overall energy efficiency improvement of 2%. Further utilisation of the waste heat will be achieved through the heating system and the system for preparing sanitary hot water during the winter season. If properly optimised, both systems can lead to annual final energy savings of 2600 MWh or 3020 MWh of primary energy savings. Although there is a 16% savings potential for the process pre-heat, the energy cost savings are not significant compared with the overall production costs. The main potential for the reduction lies in the replicability of the proposed concept, where significant cost savings can be achieved through multiplication effects. A software solution for energy management will also be required for the proper balancing and management of the recovered heat.

4.2.1. HPHE technology application for waste heat recovery in steel plants

Manufacturing of steel requires preheating of the steel billets to high temperatures before further processing. The temperature of the preheating process has to be strongly controlled in order to achieve certain structure of the material. The identified excess heat stream of the flue gas is estimated at about 20% of energy input to the furnace (or more than 4200 MWh/year) and the available waste heat potential is estimated at more than 12% of the heat input (or more than 2600 MWh/year).

One of the goals of the ETEKINA project is to reuse more than 40% of main waste heat potential of the flue gas, by using a HPHE. The preheated combustion air from the first HPHE stage (HPHE_air) is the input to the recuperator for further heating to higher temperature (over 400 °C). Flue gases after leaving HPHE_air enter second HPHE stage (HPHE_water) for heating water of the heating system of company (in winter time). The concept of the waste heat recovery by using HPHE technology for preheating of the combustion air and water for space heating in case for steel industry is shown in Fig. 9.

The design for two stages HPHE will take into consideration different and specific characteristics of working conditions for each HPHE's stage: temperature of exhaust stream in each HPHE's stages inlets and desired temperature heat sinks (temperature of combustion air and heating water). Based on these conditions, the operating temperature of the working fluid in the heat pipe can be determined and the

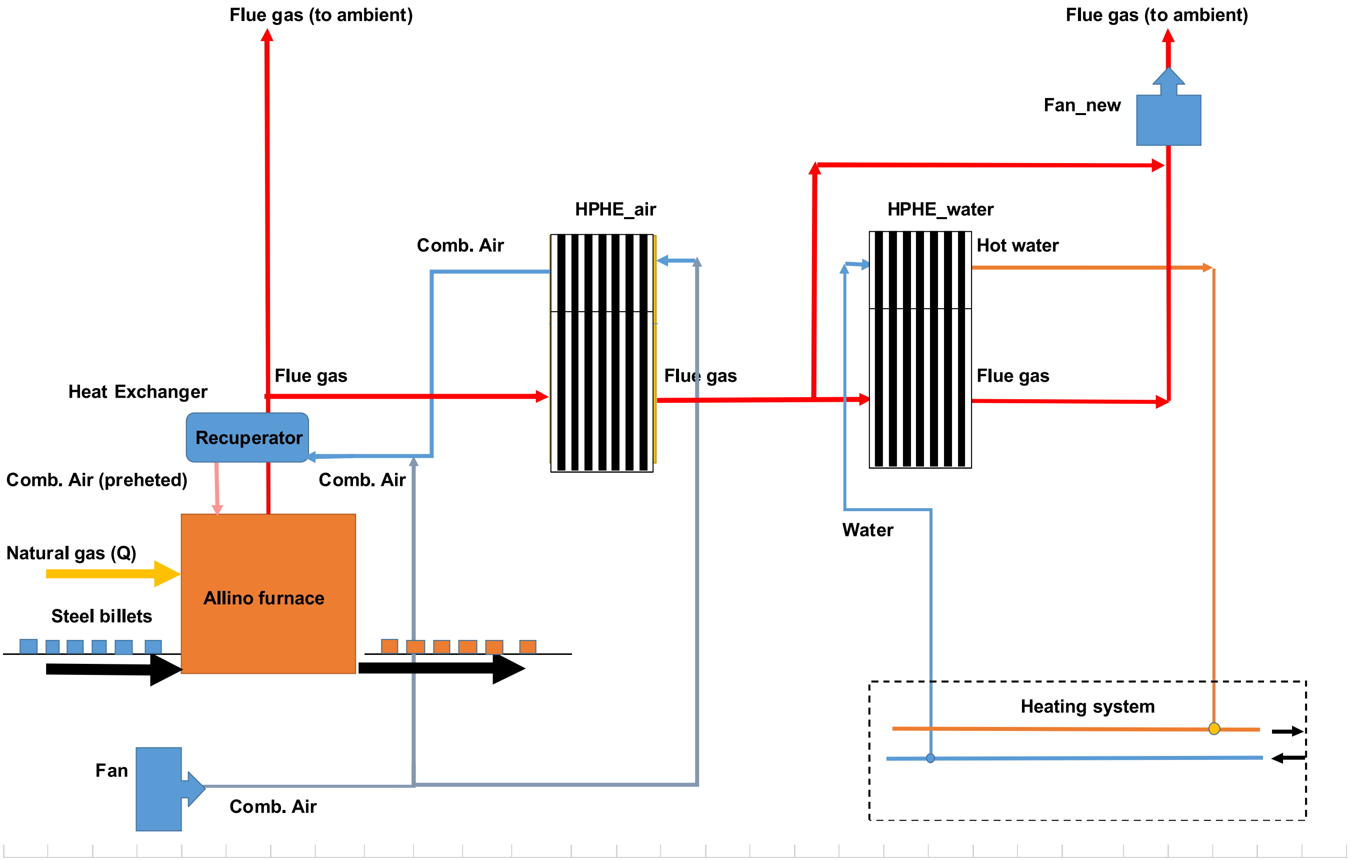


Fig. 9. Concept of the waste heat recovery in metal steel industry.

working fluid can be selected accordingly in similar procedure explained for the Aluminium plant sector case (Fig. 9).

4.3. *Tile manufacturing plant*

As introduced in the Section 2.3, different waste heat sources can be identified in the tile manufacturing plant. In ETEKINA project, the waste heat recovery identified are the exhaust fumes of the kilns, the waste heat source with the highest energy content in the plant; indeed, the exhaust gases are characterized by the highest temperatures, i.e., 245–250 °C.

The kiln exhaust gases contain pollutants which prove to be very aggressive to metal, hence discouraging heat capture through conventional heat exchangers; the heat recovery is enabled by the installation of a heat pipe based heat exchanger.

In the ceramic facility, the heat pipe based heat exchanger will be placed before the main chimney in order to recover the exhaust gases from two kilns.

The recovered heat will be transferred to the spray dryer, the heat sink identified, by means of a thermal fluid; the transfer medium that fulfils the safety and required specification of the company is water.

The suitable working temperature for the secondary stream, i.e., water, are 115 –170 °C at the HPHE inlet and outlet respectively; in this way, the tile manufacturing plant will benefit from a flexible and easy to transfer heat source.

One or two intermediate heat exchangers will be installed in parallel in order to exploit the thermal energy recovered by the heat pipe based heat exchanger heating up the air required by the spray-drier process.

The ETEKINA circuit can lead to an annual primary energy saving of 4003 MWh/y and to a reduction of 850 t/y of CO_2 emission.

4.3.1. *HPHE technology application for waste heat recovery in tile manufacturing plants*

As already introduced, the implementation of heat recovery technology in the ceramic sector is fundamental in order to improve the energy efficiency of industrial processes.

Even though many examples of energy savings technology applied to the ceramic sector have been mentioned above, few cases related to the use of HPHEs as waste heat recovery system in the ceramic sector can be find in literature [25,27].

The main challenge in the ETEKINA project is the heat recovery directly from the exhaust gases of the ceramic furnaces. Indeed, the gases are characterized by acid compounds that could condensate during the heat recovery and by a small amount of particulate that could clog up the heat exchanger.

The HPHE technology offers some advantages in comparison to the classical heat exchangers that enable this challenging heat recovery.

Thus, such a system prevents the formation of hot and cold spots in the evaporator and the condenser section; particularly, in the ceramic sector cold spots in the evaporator must be avoided in order to prevent any acid condensate.

The use of the HPHEs presents other advantages that make this system suitable for the ceramic sector.

In this waste heat recovery system, there is a complete separation between the primary and the secondary flows, i.e., exhaust gases and thermal fluid respectively, preventing any contamination between the two different streams.

Additionally, the efficiency of the HPHE is higher than of a conventional heat exchanger [28] which leads to a reduction for the space required for the installation.

Finally, the design of the HPHE tends to be more compact and with few mechanical parts. The fouling phenomenon that could occur in classical heat exchanger can be avoided by designing the heat pipe heat exchanger without any stagnation points or obstacles in the flow streamline since HPHEs offer more flexibility in designing the overall dimensions of the system. Thus, a HPHE with smooth surface of heat pipes for the same duty of a convectional heat exchanger will have smaller size since the overall heat transfer coefficient of a HPHE is much higher.

The working fluid and shell case material of the heat pipe were selected in the same procedure for the Aluminium plant case considering the exhaust and the heat sink temperatures. Distilled water is the most appropriate candidate as a working fluid, and the selected compatible shell material is stainless steel.

Thus, the HPHE enables the recovery directly from the exhaust gases of the kilns and the recovered heat will be exploited in the spray-drier.

Fig. 10 shows the sketch for the mass flows in the ceramic case where the main streams are:

- Red circuit: represents the heat source, the exhaust gases from the kilns
- Blue circuit: this is the secondary stream. The heat transfer fluid is water.

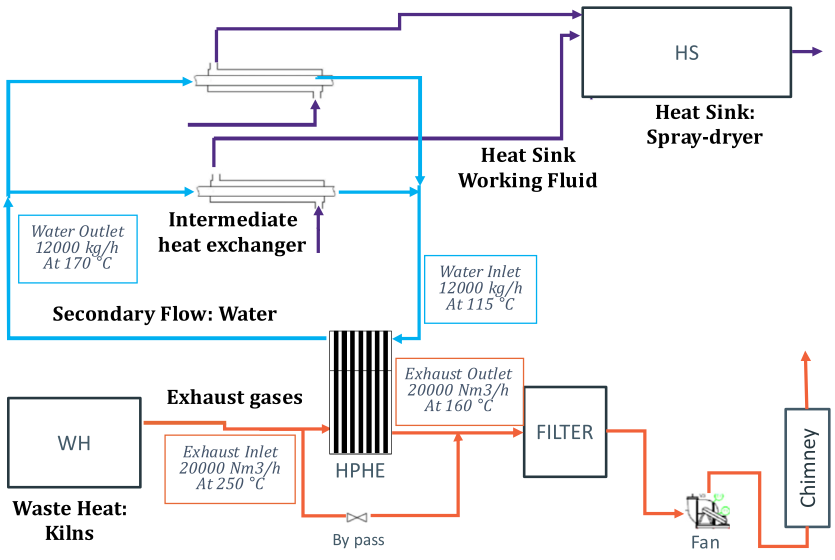


Fig. 10. Concept of the waste heat recovery in the ceramic plant.

- Purple circuit: it represents the working fluid of the spray drier process, that is air.

5. Expected impact and conclusions

The HPHE is a very efficient technology for heat recovery in challenging applications. HPHEs can be upsized to maximise the heat recovery from waste streams, however sizing the HPHE reaches a limit where any further increasing in the scale of the system will only slightly increase the duty of the unit in comparison to a great increment in the cost of the system. Therefore, HPHEs in ETEKINA project are intended to be designed to recover 40% of the waste stream within a pay-back period of less than three years. The Simple Payback Period (SPP) for the three cases investigated was selected to evaluate the solutions from an economical point of view. The SPP accounts for the time required to recover the cost of an investment taking a zero-rate interest of money. This preliminary analysis accounts for the net cash inflows during the period (monetary value of primary energy savings [30,31] and CO_2 emissions [32].

These waste heat recovery solutions present waste heat recovery values greater than 40% of the waste heat stream addressed. ETEKINA project provides primary energy savings of around 597 MWh/y, 3020 MWh/y and 4003 MWh/y with the corresponding CO_2 emissions reduction [33] by 135 t/year, 600 t/year and 797 t/year. Besides, the economic analysis shows excellent results [34] with SPPs of less than three years. The initial expected pay-back period of the initial HPHE is expected to be 32, 12, and 24 months for the demonstration sites 1, 2, and 3, respectively. The proposed solutions with this novel technology and the current project will not only provide great energy savings to the case study industries but will open the door to the replicability of the solution into other industries and sectors with similar temperatures, waste stream compositions and flow rates. These source and sink features are sufficiently diverse and characteristic to cover several kinds of processes from manifold industries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank the European Commission and the partners of the European H2020 project “Heat pipe technology for thermal energy recovery in industrial applications” (https://www.etekina.eu/, H2020-EE-2017-PPP- 768772) for their support. A reduced version of this paper was presented within The International Symposium on Energy Efficiency in Europe in the International Conference on Advances in Energy Systems and Environmental Engineering (ASEE19) the 10th of June in Wroclaw, Poland.

References

[1] EUROSTAT. Consumption of Energy. 2017 2019-02-15. Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Consumption_of_energy.
[2] European Commission, Energy roadmap 2050. COM(2011) 885 final. 2012.
[3] European Commission, COM/2017/0687 final; 2017 assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency, in Directive as required by Article 24(3) of the Energy Efficiency Directive 2012/27/EU. 2017 The Commission To The European Parliament And The Council.
[4] J. Wachsmuth, et al., How Energy Efficiency Cuts Costs for a 2-Degree Future, Fraunhofer Institute for Systems and Innovation Research ISI, 2016, p. 100.
[5] Y. Chan, R. Kantamaneni, Study on Energy Efficiency and Energy Saving Potential in Industry from possible Policy Mechanisms, ICF International, 2015.
[6] T.D. Gerarden, R.G. Newell, R.N. Stavins, Assessing the Energy-Efficiency Gap, National Bureau of Economic Research, 2015 Working Paper Series No. 20904.
[7] J. Rasmussen, The additional benefits of energy efficiency investments—a systematic literature review and a framework for categorisation, Energy Effic. 10 (6) (2017) 1401–1418.
[8] M. Schulze, et al., Energy management in industry – a systematic review of previous findings and an integrative conceptual framework, J. Clean. Prod. 112 (2016) 3692–3708.
[9] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, S.A. Tassou, Waste heat recovery technologies and applications, Therm. Sci. Eng. Prog. (2018) 268–289 6, doi: 10.1016/j.tsep.2018.04.017.
[10] E. Woolley, Y. Luob, Simeone A, industrial waste heat recovery: a systematic approach, Sustain. Energy Technol. Assess. 29 (2018) 50–59.
[11] M. Saghafifar, A. Omar, K. Mohammadi, A. Alashkar, M. Gadall, A review of unconventional bottoming cycles for waste heat recovery: part I – analysis, design, and optimization, Energy Convers. Manag. 198 (2019), doi: 10.1016/j.enconman.2018.10.047.
[12] Confindustria Ceramica report.
[13] European Comission. Reference document on best available techniques in the ceramic manufacturing industry. 2007.
[14] A. Mezquita, J. Boix, E. Monfort Gimeno, G. Mallol Gasch, Energy saving in ceramic tile kilns: cooling gas heat recovery, Appl. Therm. Eng. 65 (2014) 102–110, doi: 10.1016/j.applthermaleng.2014.01.002.
[15] B. Peris, J. Navarro-Esbrí, F. Moles, A. Mota-Babiloni, Experimental study of an orc (organic rankine cycle) for low grade waste heat recovery in a ceramic industry, Energy (2015), doi: 10.1016/j.energy.2015.03.065.
[16] J. Beltran, Cogeneration systems in the ceramics tile sector, in: Proceedings of the Workshop on New Technologies for the Rational Use of Energy in the Ceramics Tiles Industry, DG for ene, EC. Spain: Castellon de la Plana, 1994.
[17] European Comission. Reference document on Best Available Techniques in the Smitheries and Foundries industry. 2005.
[18] G. Cusano, M.R.G., F. Farrell, R. Remus, S. Roudier, L. D. Sancho, Best Available Techniques (BAT) Reference Document for the main Non-Ferrous Metals Industries. 2017.
[19] P. Enderle, O. Nowak, J. Kvas, Potential alternative for water and energy savings in the automotive industry: case study for an Austrian automotive supplier, J. Clean. Prod. 34 (2012) 146–152.
[20] European Commission-JRC. Best Available Techniques (BAT) Reference Document for Iron and Steel Production, 2013.
[21] S. Almahmoud, H. Jouhara, Experimental and theoretical investigation on a radiative flat heat pipe heat exchanger, Energy 174 (2019) 972–984 Elsevier Ltd., doi: 10.1016/j.energy.2019.03.027.
[22] A. Faghri, Heat pipes: review, opportunities and challenges, Front. Heat Pipes 5 (1) (2014), doi: 10.5098/fhp.5.1.
[23] H. Jouhara, et al., Experimental and theoretical investigation of a flat heat pipe heat exchanger for waste heat recovery in the steel industry, Energy 141 (2017), doi: 10.1016/j.energy.2017.10.142.
[24] B. Delpech, B. Axcell, H. Jouhara, Experimental investigation of a radiative heat pipe for waste heat recovery in a ceramics kiln, Energy 170 (2019) 636–651 Elsevier Ltd., doi: 10.1016/j.energy.2018.12.133.
[25] B. Delpech, M. Milani, L. Montorsi, D. Boscardin, A. Chauhan, S. Almahmoud, B. Axcell, H. Jouhara, Energy efficiency enhancement and waste heat recovery in industrial processes by means of the heat pipe technology: case of the ceramic industry, Energy 158 (2018) 656–665 Elsevier Ltd., doi: 10.1016/j.energy.2018.06.041.
[26] H. Ma, L. Yin, X. Shen, W. Lu, Y. Sun, Y. Zhang, N. Deng, Experimental study on heat pipe assisted heat exchanger used for industrial waste heat recovery, Appl. Energy 169 (2016) 177–186, doi: 10.1016/j.apenergy.2016.02.012.
[27] B. Axcell, H. Jouhara, Experimental investigation of a radiative heat pipe for waste heat recovery in a ceramics kiln bertrand delpech, Energy 170 (2019) 636–651.
[28] H. Jouhara, A. Chauhan, T. Nannou, B. Delpech, L.C. Wrobel, Heat pipe based systems – advances and applications, Energy 128 (2017) 729–754.
[29] G. Williams, (2016) Global heat pipe industry report application and regional growth forecast 2021, Egypt Business Directory. Available at: https://www.egypt-business.com/ticker/details/1647-global-heat-pipe-industry-report-application-and-regional-growth-forecast-2021/69066 (Accessed: 7 July 2019).
[30] EUROSTAT. Natural gas price statistics. 2018 13/03/2018. Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics.
[31] Statistical Office Of The Republic Of Slovenia. Gas price Slovenia. 2018. Available from: http://pxweb.stat.si/pxweb/Dialog/varval.asp?ma=1817502S&ti=&path=../Database/Repozitorij_SLO/&lang=2.
[32] Business Insider. Carbon price per ton from; 2018. Available from: http://markets.businessinsider.com/commodities/co2-emissionsrechte.
[33] R. Edwards, J.F. Larive, D. Rickeard, W. Weindorf, S. Godwin, H. Hass, A. Krasenbrink, L. Lonza, H. Maas, R. Nelson, A. Reid, K. Rose, H. Hamje, Well-To-Tank Report version 4.a: JEC Well-To-Wheels Analysis Joint Research Center, 2014.
[34] D. Chiaroni, et al., Introducing a new perspective for the economic evaluation of industrial energy efficiency technologies: an empirical analysis in italy, Sustain. Energy Technol. Assess. 15 (2016) 1–10.