Radiant waste heat recovery from steelmaking and glass industry

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Abstract. This paper tackles the problem of industrial waste heat recovery through an unexploited heat transfer mechanism: thermal radiation. Energy intensive industries have a considerable potential of unused radiant heat, which cannot be recovered through existing methods. That potential energy is quantified for the main identified industries: steel and glassmaking. Then, a radiant heat capturing device allowing high temperature heat capture is designed according to process requirements. Finally, recoverable heat is estimated and potential uses are proposed.

1 Introduction

Global warming is a clear threat and European policies define a "long-term strategy for the reduction of greenhouse gas emissions, as requested by the European Council in March 2018, confirming the European lead in global climate action. It presents a vision to achieve climate neutrality by 2050, through a fair transition encompassing all sectors of the economy"1]. Industries, as large energy consumers, play a key role on this transition in which industrial waste heat recovery is a critical point to reduce fossil fuel consumption. Although industrial waste heat capture has increased in many sectors, sources are typically combustion gases, water circuits etc., whereas radiant heat is still unused as a source of waste heat. Radiant heat is not present in all industrial sectors, but in the case of energy intensive industries, such as steelmaking and glass manufacture, the quantity of this type of heat seems enough for its recovery to become worthwhile.

Besides, radiant heat emission poses a threat for surrounding machinery and staff, as the continuous exposure to this heat has a negative impact on working conditions, resulting ultimately in physical damage 2]. Consequently, industries are often forced to develop solutions specifically for radiation shielding.

A radiant heat recovery system is proposed in this paper, which both solves the problem of radiant heat emission and seizes the opportunity of recovering currently unused waste

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heat. The use of this system would lead to the increase of overall energy efficiency and sustainability, as well as to improved working environment and ergonomics. Ultimately, it would result in a more competitive industry.

However, the recovery of radiation heat requires specific devices and systems that are not developed yet. Solar thermal collectors are the nearest technological solution, but they focus on capturing radiation at a different range of the electromagnetic spectrum: sunlight peaks at visible range, while radiant heat available in industries has its peak shifted towards the infrared region due to its lower temperature compared that of the sun, according to Wien's displacement law (1).

$$\lambda_{\max} = \frac{b}{T} \tag{1}$$

where T is the absolute temperature in Kelvin and b, is Wien's displacement constant, equal to $2.89 \cdot 10^{-3}$ mK.

Hence, heat transfer conditions are different and solar thermal collectors would not work effectively. Moreover, there are several process-related barriers hindering direct application, such as space limitations and environmental conditions. Consequently, existing technology in the field of solar energy cannot be used for industrial waste heat recovery.

Furthermore, there is no commercial equipment developed for radiant heat capture in industrial environments. Only a few patents have been found covering this kind of waste heat recovery, revealing a very early stage of development of the required technology. Radiant heat capture is often covered in a merely theoretical and superficial manner, as in EP2403668 (A2) 3]. In conclusion, there is a need to design a new kind of heat recovery system, which is described in this paper.

2 Analysis of industrial processes with high radiant heat potential

A parameter with critical importance in heat transfer by radiation is temperature, as the radiant emittance, i.e. the total energy radiated by a surface, is directly proportional to the fourth power of its temperature, as derived from the Stefan-Boltzmann law (2).

$$j^{\star} = \sigma T^4 \tag{2}$$

where T is the absolute temperature in Kelvin and σ the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8}$ $Wm^{-2}K^{-4}$. The effect of temperature can be clearly observed in Fig. 1, in which black body total emittance (j^*) is plotted as a function of temperature:

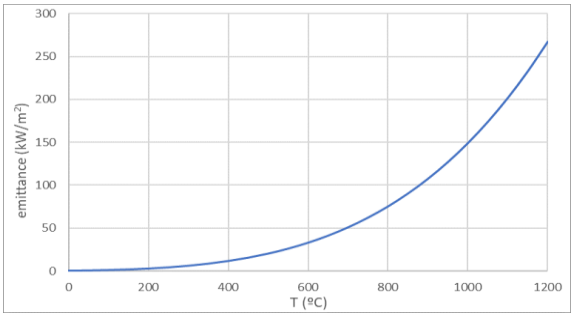

Fig. 1. Total emittance of black body as a function of temperature.

Fig. 1 shows clearly the influence of temperature in heat transfer by radiation (i.e. emittance). For example, the energy irradiated at 1000°C is approximately twice the amount emitted at 800°C. Additionally, it shows how radiant energy becomes irrelevant at temperatures below 500°C approximately. Therefore, processes with lower temperatures are not considered in this paper as potential applications.

Another important parameter in heat transfer by radiation between grey bodies (non-ideal emitters, which is the idealization commonly assumed for most opaque materials) is emissivity, meaning the effectiveness in emitting thermal radiation. It depends on the type of material, the type of surface finish (polished-glossy/unpolished-matte) and on temperature. In this case, higher values also imply larger amount of emitted energy and thus high emissivity is sought in the emitting body.

Steelmaking, glassmaking and metal forging industries have been identified as the main sectors with radiant heat sources in which such high temperatures and emissivities are found along their production processes. However, apart from these parameters, annual production and process continuity are key to achieve an optimum heat recovery. In forging processes, temperatures above 1000°C are reached, but the annual production of an average facility (20000 t/year, 4]) is not sufficient to offer an attractive amount of radiant waste heat. Therefore, steelmaking and glass manufacturing were selected for this study as the main sectors in terms of radiant heat potential.

Regarding steelmaking, three main points of the process were identified which offer considerable levels of available radiant heat: the section between continuous casting outlet and the oxy-cutting, the rolling stage where the final shape is given to steel products and the final cooling area after the rolling mill stage. Additionally, in facilities where wire rod is produced, all distance traversed by the rod and mainly, the final step when it is curled, are also potential points for radiant heat recovery. All those points share a characteristic that make them suitable for the selected application: the steel reaches high temperatures and thus, radiant heat is released to the surrounding ambient. Nonetheless, the radiant heat emission is continuous in just one of them: the section located between the continuous casting outlet and oxy-cutting, in which billets/blooms/slabs have not been cut yet. The continuity of the process is critical for a stable heat supply. Additionally, at that point steel is incandescent, with surface temperatures as high as 1000°C, resulting in a maximum radiant heat emission. Therefore, that specific stage is selected as the reference case for this study.

Similarly, for glassmaking, different processes were analysed with the purpose of identifying radiant heat recovery opportunities. In flat glass production process glass is not accessible until its temperature is below the considered limit for substantial radiation emission, so it was discarded for radiant heat recovery. Bottle and jar production process is more favourable for this kind of waste heat capture. More specifically, the line located between the moulding stage and the annealing furnace, where bottles are exposed at temperatures around 600 ºC, is identified as the optimal heat radiation recovery point in this sector. In glass industries, temperatures are lower than the ones in the steelmaking case, but emissivity values are considerably higher.

Błąd! Nie można odnaleźć źródła odwołania. shows the main parameters which are relevant in radiant heat emission, allowing heat potential estimation. All presented data was collected from two facilities representative of average steelmaking and glass container manufacturing plants: a steel mill in Bizkaia (Spain) and a typical glassmaking factory in Europe 5].

Table 1. Parameters of radiant heat in representative steelmaking and glassmaking facilities.

Parameters	Steel continuous casting	Glassmaking
Emitter surface temperature, °C	1000	600
Emissivity	0,82	0,92
Radiant surface, m^2 per linear m	0,72	0.50
Radiant power, kW/m	88	15
Operating hours/year	5000	8500
Production rate, t/h	150	23,5
Total emitting line length, m	24	80
Radiant heat available, kWh/t	14	52
Yearly heat available, MWh/year	10549	10315

Average sized emitter bodies were considered as the calculation basis for each case: in steelmaking, a 240 x 240 mm billet was taken as a reference and, in glassmaking, a standard 750 ml bottle with height of 290 mm and a base diameter of 62 mm. These data were used for the calculation of emitting surface per linear metre, and then for radiant power per linear metre. On the other hand, radiant power by surface unit was calculated according to Stefan-Boltzmann law (2) for grey bodies (using emissivity as a factor). Global energy potential results were calculated by using production data.

It should be highlighted that in glassmaking, the energy to mass ratio is higher. The reason for that is that emitting surface to mass ratio is notably higher in glass containers (high surface, low density and hollow semi-transparent solid) compared to steel products (solid opaque body, high density material). Nonetheless, in both cases a similar radiant heat power is ultimately released over a year, due to production rates.

The steel sector in Europe produces on average 170 million tonnes of steel per year at more than 500 steel production sites across 24 EU member states 6]. As for glassmaking in Europe, about 21.5 million tonnes of glass containers were produced in 2017 7]. According to data in Table 1, the overall radiant heat potential in Europe is estimated roughly in 1 TWh/year for glass container manufacturing sector and 2 TWh/year for steelmaking (considering only the section between continuous casting outlet and oxy-cutting).

3 Radiant heat capturing device design

A heat capturing device was designed based on the characteristics of the previously selected reference case: the continuous casting of steel. The design was focused on maximizing efficiency and thus heat recovery, while considering process boundaries. The main parameters directly related to the efficiency of the device are the following:

- **View factor:** In radiative heat transfer, view factor $F_{A \rightarrow B,}$ is the proportion of radiation which leaves surface A and reaches surface B. This parameter is critical for the efficiency since, even if the emitter and capturing device were ideal, if the emitted radiation does not get to the absorber surface it will be lost directly.

This can be observed in Fig. 2, which shows view factors calculated for two examples corresponding to the installation of different tunnel-shaped collectors (2) over glass bottle/jar producing lines (1):

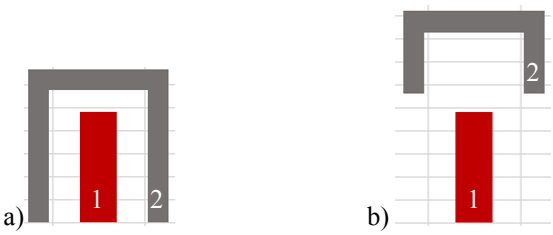

Fig. 2. Front view of different tunnel-shaped collectors over bottle/jar line, a) Ideal case: $F_{1\to2}$ = 0.88, b) Conservative case: $F_{1\to2}$ = 0.18

In the ideal case (a) bottles are completely enclosed by the collector and thus, almost all the emitted radiant heat, reaches the absorbing walls. However, that alternative is not always possible due to process boundaries related to accessibility and visibility requirements, which leads to case b. In this case, the collector is elevated over bottles and 82% of the emitted radiation is directly lost ($F_{1\to2}$ = 0.18). Fig. 3 shows a chart displaying a full series of cases demonstrating this effect of heat collector elevation on view factor.

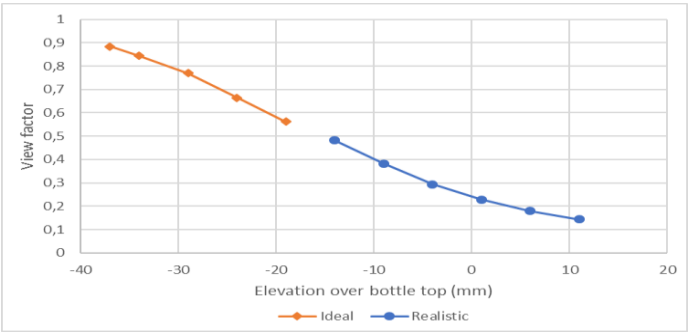

Fig. 3. Heat capturing device elevation effect on view factor. Glass industry case.

In Fig. 3, elevation is calculated having as a reference the glass bottle top and the heat collector bottom, meaning that elevation 0 corresponds to the case in which both are at the same level. Realistic cases cover a range of different elevations corresponding to the same collector geometry (the one shown in Fig. 2, case b). In ideal cases, the top of the collector remains at the same position, extending the walls towards the floor and thus, increasing the view factor until the maximum, corresponding to the bottom of the collector at the same level as the bottom of the emitter (maximum enclosure, Fig. 2, case a). As it is shown, if collector lateral walls cover emitter sides forming an enclosure, view factors can reach high values, near 0,9. On the contrary, other geometries can lead to view factors as low as 0.1. Therefore, view factor has a critical effect on system efficiency.

- **Geometry:** as stated before, heat capturing device geometry is directly related to view factor and thus to efficiency. Therefore, the shape of the system is also a critical parameter.

Initially, heat concentration using reflectors was considered for the collector design. However, target industrial processes have strict space limitations which pose a barrier for this solution. Different compound parabolic geometries were tested in Zemax, a specific ray tracing software. The percentage of emitted radiation which gets to the receptor was calculated. Results were poor for this alternative as space restrictions did not leave room for proper optical design. Consequently, the concentration system design was dismissed.

Calculations showed better results for enclosing geometries in which thermal radiation gets directly to the heat absorbing walls of the collector. A tunnel shape was finally selected, due to its robustness and high view factors. In the reference process (continuous casting outlet) almost-complete enclosure is possible, obtaining excellent view factors around 0.88, as in Fig. 2, case a. This leads to minimum thermal radiation loss.

- **Coating:** Thermo-optical properties of the heat capturing surface are a critical parameter in radiative heat transfer efficiency. Therefore, a coating was incorporated to the design to increase thermal absorptivity and thus, efficiency.

Several requirements were considered: ease of application, full availability in Europe, eco-friendliness and ability to withstand extreme conditions at industrial environments (high temperatures, continuous production, aggressive environment, etc.). A detailed study was carried out to identify commercially available solutions. Three products were initially identified: Pyromark (Tempil, USA) 8], BGHitCoat (BG SYS HT s.r.o., Czech Republic) 9] and HiE-Coat™ (Aremco Products, USA) 10]. However, none of those satisfies all the requirements mentioned above, thus a formulation of an in-house coating was developed.

The new paint is based on silicate aqueous binders (water-glass) where ceramic nanoparticles are incorporated (based on aerospace applications where radiative properties are an asset). The silicate acts as binder for the coating whereas the nanoparticles are the absorptivity enhancer. Thermo-optical properties were measured and compared with the available commercial coatings. The new paint offers similar high emissivity/absorptivity values in the infrared, and particularly high and constant absorptivity values in the range of interest corresponding to this application (peak wavelengths at 2–4 μm).

Table 2. Summary of coating properties from different providers.

Coating	Emissivity/Absorptivity (@ Temperature, °C)	Wavelength Range (μm)	Measurement Method
New paint	0.92–0.89 (room T – 500)	2–20	Spectral normal emissivity
BGHitCoat	0.93–0.98 (500–1100)	2–22	-
HiE-Coat™	0.92–0.83 (800)	2–25	Spectral normal emissivity

A preliminary endurance test was also performed by exposing test samples at high temperature for prolonged periods both in laboratory and real environment in a steel mill. The coating showed good adherence and no delamination. Moreover, thermo-optical properties remained constant after this thermal exposure, showing high stability.

- **Materials:** the heat capturing device can be exposed to high temperatures, so materials are required to maintain its mechanical integrity without overcoming their yield strength. Recommended high temperature resistant materials are, among others, AISI 347 and 321 11]. AISI 347 was tested at extreme temperatures together with the aforementioned paint, showing positive results in terms of degradation resistance.
- **Heat transfer fluid:** the design is flexible in terms of heat transfer fluid, which can be water ($T < 100$°C), thermal oil ($T < 450$°C) or even molten salts ($T > 450$°C). The selection depends greatly on the final use of the recovered heat, which defines the required temperature level.
- **Insulation:** when working at high temperatures, heat losses become relevant and proper insulation is needed. To maintain modularity and compact sizing, a low conductivity ceramic fibre insulation is selected, allowing small insulation thickness.

4 Recovered radiant heat estimation

All the characteristics described in the previous section were considered for heat capture efficiency calculation. The system was modelled with two simulation tools: Dymola and ANSYS-Fluent. As a result, heat recovery efficiency for steel continuous casting reaches values around 70%, whereas this efficiency drops to around 35% in the case of glassmaking. Results were cross-validated by both software, confirming good calculation accuracy.

Energy recovered in both sectors differ, heavily influenced by process parameters. One of the factors with the highest influence is the view factor, which is restricted by process requirements, such as space limitations due to surrounding machinery or accessibility. These restrictions were higher in the case of glassmaking, for example, accessibility requirements for periodic quality controls or bottle-visibility needs for inspections. The fulfilment of these requirements results in lower view factor values and thus, higher radiation losses and lower recovery efficiency. Moreover, parameters as lower temperature level and yearly production, contributed to the lower efficiency.

The application of heat recovery efficiency leads directly to the final recovered heat results, as shown in Table 3.

Table 3. Estimated radiant heat recovery by the tunnel capturing device.

Parameters	Steel continuous casting	Glass
Radiant heat available, kWh/t	14	52
Heat recovery efficiency, %	70	35
Net heat recovered, kWh/t	10	18
Yearly net heat recovered, MWh/year	7385	3610

5 Possible applications of captured heat

One of the key questions that arises when waste heat recovery is planned is the use of captured heat. Several parameters are decisive in choosing the final application, among which temperature level is key. The device presented in this paper allows flexible heat recovery at different temperatures, widening the range of final consumptions choices. The following are the main identified applications for recovered waste heat:

• **Direct use in productive process**. in glass making facilities, both mineral raw material (silica sand, soda and limestone) and glass cullet could be preheated and the increase of temperature of the material fed to the furnace would be a clear and direct energy saving measure. However, the effectiveness of a heating system for a particulate solid using a thermal fluid is rather low. Besides, due to the size of glass bottle manufacturing facility, distance between the point where bottles are produced (heat capture) and the raw material feeding point to the furnace (use of captured heat) is high and will mean a costly installation and partial loss of captured heat. A similar situation occurs for scrap heating at steelmaking facility. Therefore, raw material preheating is not the optimum use for recovered heat. However, heat recovered could be used more efficiently for preheating combustion air used in glass and steel furnaces (re-heating and thermal treatment furnaces).

• **Heating of offices and workshops**. Distance between radiant heat source and use of the captured heat is the main parameter for a cost-effective solution. This use would result in energy savings in winter. In summer, heat could also be used in absorption refrigeration to obtain cooling. Low-temperature recovered heat would be sufficient for this application, leading to high thermal efficiency.

• **Electricity production by means of an Organic Rankine Cycle (ORC).** High temperatures, which can be obtained by means of the proposed heat collector, lead to higher energy efficiency in this application. However, calculations show that radiant heat potential

is not enough by itself to get good electricity production efficiency through ORC. Efficiencies around 17% (electricity production vs heat supply) can be obtained for heat sources with an installed power of 10 MW_{th} 12]. According to the previous calculations, this power cannot be reached only from radiant heat at steelmaking/glassmaking reference processes. Recovered radiant heat from reference processes should be used together with additional heat sources, which could be other radiant heat sources or larger energy potential processes, such as exhaust gases from furnaces.

• **Sale of heat to a district heating network.** Again, distance between the production facility and the district heating network is a key parameter for cost-effectiveness. The heat transfer fluid for the radiant heat capture device could be directly water, simplifying the design. The industry would obtain incomes for sold heat.

6 Conclusions

Thermal radiation is a form of industrial waste heat that can be considered exploitable. Steelmaking and glass container manufacturing processes show the highest radiant heat potential. More specifically, within steelmaking process, the section between continuous caster outlet and oxy-cutting has ideal conditions for radiant heat recovery.

A radiant heat capturing device was designed, taking high potential processes as a reference. A view factor maximizing geometry was selected and a new high absorptivity coating was developed for the heat capturing surface. All these features lead to theoretical efficiencies around 70%, calculated through thermal simulation software.

All the results presented in this paper, such as calculated theoretical efficiencies, will be validated through experimental characterization. To this end, a laboratory-scale heat collector prototype and test rig have been constructed replicating the continuous casting process.

As for captured heat use, there are a number of possible applications. In general, efficiency would increase if captured radiant heat was used together with other industrial waste heat sources, such as exhaust gases.

It is expected that in a near future, with higher fossil fuel prices, higher CO_2 emission costs and better working condition requirements, radiant heat recovery will play an important role in improving steel and glass industries.

References

1. European Commission, *Our Vision for A Clean Planet for All* (2018)
2. Ideara, *Radiaciones ópticas artificiales. Factores relacionados con la fuente y las medidas de control* (2013)
3. EP2403668 (A2) *Energy recovery in hot strip mills by converting the cooling heat of the continuous casting plant and the residual heat of slabs and coils into electrical energy or otherwise utilizing the captured process heat* (2012)
4. SIFE, *Benchmarking energético en las empresas de forja por estampación* (2015)
5. TASIO project, *D2.1 Energetic flowchart for cement, glass, steel industries and petrochemical sectors* (2016)
6. EUROFER, *Annual report 2018*, 3 (2018)
7. Glass Alliance Europe, *Production Breakdown by Sectors* (2017)
8. K. Ho Clifford, A. Ambrosini, M. Bencomo, A. C. Hall, T. Lambert, A. R. Mahoney, *Characterization of Pyromark® 2500 for High-Temperature Solar Receivers* (2012)

9. BG HitCoat® – Technical specifications, *Physical and mechanical properties of BG HITCoat® Composite.*
10. Aremco, *High Temperature*, *High Emissivity Coatings*
11. Allegheny Ludlum Corporation, *Stainless Steels: Types 321, 347 and 348 (UNS S32100, S34700 and S34800)*, Technical data blue sheet
12. PITAGORAS project, Sustainable urban Planning with Innovative and low energy Thermal And power Generation fröm Residual And renewable Sources. FP7-ENERGY – Specific Programme "Cooperation": Energy. Grant agreement ID: 314596