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# Proof of concept to recover thermal wastes from aluminum electrolysis cells using Stirling engines

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A B S T R A C T

The production of aluminum is a low energy-efficient industrial process. In fact, almost half of its energy demand is lost under the form of heat along the production line. For this reason, aluminum producers are interested in improving energy efficiency of their smelters by recovering the thermal losses. It is well known that a significant loss of energy occurs across the sidewalls of the electrolysis cells. This paper proposes a proof of concepts where the sidewall thermal wastes are used to drive Low Temperature Differential (LTD) Stirling engines. To estimate the losses, a heat transfer study is implemented; heat conduction coupled with mixed convection and radiation is evaluated by using the OpenFOAM Computational Fluid Dynamic (CFD) software. Then, a parametric study is performed to analyse cell working conditions under which thermal wastes could be recovered. The heat flux and the temperature of the thermal wastes are used to judge the utilization of possible Stirling engine technologies. Two scenarios are studied: (i) a plane heat collector coupled to the radiative sidewall and (ii) a plane heat collector in direct thermal contact with the cell sidewall. It is demonstrated that the recovery of the wastes by radiation is technically feasible and it does not threaten the safety of the smelter; furthermore, the losses can power some Stirling engines given in the open literature. Therefore, the recovery of the radiative wastes and the further conversion by means of the Stirling engine is an interesting solution to improve the aluminium smelter energy efficiency.

## 1. Introduction

The aluminum production is one of the most energy intensive industrial sectors. The only known-to-date method to produce primary aluminum is the Hall-Héroult process (independently discovered by Charles Martin Hall and by Paul Héroult in 1886), where alumina ($Al_2O_3$) is reduced to aluminum by electrolysis [1]. From a theoretical view point, such a process requires 6 $MWh_{el}/ton_{Al}$; nevertheless, the actual energy demand in aluminum smelters is much higher, ranging between 11 and 15 $MWh_{el}/ton_{Al}$.

To understand the differences between theoretical and real plants energy demand, a detailed energy balance of the pot (i.e. the electrolysis cell producing aluminium) should be performed. According to the data found in the literature [2–4], about half of the energy demand (~44.2%) is effectively required to produce aluminum, while the remaining is lost along the production line. Several mechanisms are responsible of these losses: secondary (endothermic) reactions occurring in the electrolysis bath, the production of hot gases in the pot, the electrical losses in the busbars (i.e., anode-cathode connectors), the frequent openings of the cells and the thermal losses across pot sidewalls [3,5]. Among these losses, the most notable are those due to the high temperature of the gas (~16.3% of the energy demand) and those of the sidewalls (~21.2%).

It is apparent that the analyses of heat waste recovery techniques are of primary importance for aluminum producers; they could be recovered and converted into useful work [6]. Although the most important are of the same order of magnitude, the majority of the works in the open literature is focused to recovering heat wastes from the hot gases. Such a recovery is interesting; it is performed outside the smelter; hence, it does not threaten the plant's safety. Moreover, the temperature of this source (90–120 °C, depending on the season) is well suited to power Organic Rankine Cycle (ORC) engines [2–4]. Notwithstanding, ORCs are not often employed; the high costs and the low returns of investment make this technology economically unattractive for most aluminum producers [7]. In addition, the use of organic fluids in this type of industry is not welcomed.

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**Nomenclature**

*Letters*

| | |
|---|---|
| $A$ | area [$m^2$] |
| $D$,$d$ | diameter [m] |
| $F_{ij}$ | view factor [–] |
| $f$ | coefficient of Eq. (4) |
| $g$ | parameter of Eq. (9) |
| $h$ | convective heat transfer coefficient [$W\,m^{-2}\,K^{-1}$] |
| $I$ | turbulent intensity [–] |
| $k$ | turbulent kinetic energy [$m^2\,s^{-2}$] |
| $k$ | thermal conductivity [$W\,m^{-1}\,K^{-1}$] |
| $l$ | mixing length [m] |
| Nu | Nusselt number [–] |
| $P$ | pressure [Pa] |
| $P$ | perimeter [m] |
| Pr | Prandtl number [–] |
| Q | radiative power [W] |
| $q$ | heat flux [$W\,m^{-2}$] |
| $R$ | gas constant [$J\,kg^{-1}\,K^{-1}$] |
| Re | Reynolds number [–] |
| $r$ | parameter of Eq. (9) |
| $S_{ij}$ | strain rate tensor [$s^{-1}$] |
| $T$ | temperature [°C] |
| $t$ | temporal coordinate [s] |
| W | useful power [W] |
| $U$,$u$ | velocity [$ms^{-1}$] |
| $x$ | spatial coordinate [m] |
| $y^+$ | dimensionless distance from the wall |

*Greek letters*

| | |
|---|---|
| $\beta$ | volumetric thermal expansion coefficient [$K^{-1}$] |
| $\delta$ | Kronecker delta |
| $\varepsilon$ | dissipation rate [$m^2\,s^{-3}$] |
| $\varepsilon$ | emissivity [–] |
| $\eta$ | thermodynamic efficiency [–] |
| $\theta$ | dimensionless temperature [–] |
| $\mu$ | shear viscosity [Pa s] |
| $\nu_t$ | turbulent viscosity [$m^2\,s^{-1}$] |
| $\xi$ | dimensionless space coordinate [–] |
| $\rho$ | density [$kg\,m^{-3}$] |
| $\sigma$ | Stefan-Boltzmann constant [$W\,m^{-2}\,K^{-4}$] |
| $\psi$,$\Psi$ | general variable |
| $\omega$ | turbulence frequency [$s^{-1}$] |

*Subscripts*

| | |
|---|---|
| $\infty$ | free stream |
| $c$ | collector |
| $H$ | free stream |
| $m$ | maximal |
| $o$ | outlet |
| $s$ | surface |
| $sw$ | sidewall |

The recovery of the heat losses from the sidewalls of the pots has been scarcely studied [5]. The temperature on the pot external surfaces varies between 200 and 350 °C; therefore, these thermal potentials are important from both energetic and exegetic viewpoints [8]. However, the recovery is challenging, essentially amongst other because it is difficult to access as these portions of the pots are underneath the working operator area; the wall surfaces of interest are confined to a restricted space; the high concentration of both aluminum and alumina particles makes the smelter environment chemically reactive (thus, the choice of heat recovery systems must be limited to those using non-reactive fluids). In parallel to these drawbacks, the recovery and the conversion of the thermal wastes must not affect the electrolysis process, which is the main concern for aluminum producers. Few systems respecting these requirements have been proposed in the open literature. Namboothiri et al. [9] have designed an air heat exchanger to be installed directly onto the external pot walls; however, the main purpose of this work is not devoted to recover waste heat, but to control the delicate cell heat balance. The use of thermoelectric modules has been proposed too [10,11]; however, their low thermodynamic efficiency (around 7%) makes their use a poor waste-heat recovery option.

Herewith, the evaluation of sidewall thermal losses and their conversion rate into mechanical power using Stirling engines is presented. To estimate heat losses by conduction, convection and radiation a series of CFD simulations are carried out. To this aim, version 5.0 of OpenFOAM is used and the calculation schemes are validated. Electrolysis cell conditions under which the heat recovery can be maximized are parametrically studied. As a proof of concept, the use of the Stirling engines as energy conversion systems is investigated. Several reasons justify the choice of these technologies: they can be driven by any form of heat transfer (conduction, convection and radiation); the working fluid is a gas, such as argon or helium, making their use safe in aluminium smelters; they can operate under relatively low thermal potential differences and they can be dimensioned to produce power levels ranging from few watts up to several kilowatts [12–14].

This work considers the following two scenarios: (i) it is supposed that the engine has a plane heat collector that recovers energy only by radiation; (ii) the same heat collector is placed in direct thermal contact with the pot sidewall. Due to the structure of the sidewalls and the presence of air ventilation nozzles, the CFD modelling approach must consider three modes of heat transfer, i.e. conduction, convection and radiation. Appropriate Stirling engines are then selected from the open literature and thus, their estimated efficiencies are used to determine the available mechanical power. It should be mentioned that the nozzle cooling system used to control the temperature of the pot sidewalls can be applied to cool the Stirling engines. Nevertheless, this system will not require mayor modifications other than a partial reduction on the air mass flow rate, because the Stirling engine will reject less heat than that collected by radiation from the whole sidewall. In this document the changes of the actual cooling system are not addressed. The final choice of the most suitable scenario is discussed by considering the engine conversion rate and possible effects on the safe operation conditions of electrolysis cells.

## 2. Cooling the pots in aluminum smelters

The production of aluminum by electrolysis takes place in several reactor units, commonly called pots. The number of pots in a conventional smelter can reach few hundreds. The challenge for aluminum producers is to preserve the working conditions of all the pots simultaneously, since they are electrically connected in series through busbars. The temperature of the pot sidewalls constitutes a critical variable. To avoid high temperature concentration zones, it is controlled by means of several air cooling jets. To this aim, air flows at about 20 °C cool the sidewalls, whose temperatures may vary between 200 and 400 °C. It is thus obvious that large amounts of thermal energy are lost by convection and radiation.

The aluminum smelter energy demand is about 11–15 $MWh_{el}/ton_{Al}$ and the aluminum production of the Canadian industry ranges between 100 and 600 $kton_{Al}$/year. According to the pot energy balances