Light Metals 2012 *Edited by: Carlos E. Suarez*
TMS (The Minerals, Metals & Materials Society), 2012

ELECTROLYTIC CELL GAS COOLING UPSTREAM OF TREATMENT CENTER

SOLIOS ENVIRONNEMENT, El Hani Bouhabila[1], Bernard Cloutier[2], Thierry Malard[1], Philippe Martineau[2], Hugues Vendette[2]
[1] 25-27 Boulevard de la Paix, Saint-Germain-en-Laye, 78100, FRANCE
[2] 625 President-Kennedy Avenue, Suite 1400, Montreal, Qc, H3A 1K2, CANADA

Keywords: Aluminum reduction, emission control, GTC, temperature control, heat exchanger

Abstract

The general use of high amperage cells in the last decade has created new challenges for Gas Treatment Centers (GTCs). Aluminum production capacity increases proportionally with the applied electric intensity. This leads to more waste heat by joule's effect which increases the cell outlet gas temperature. The cell gas temperature also depends on the ambient temperature. In hot climates, gas temperature at the cell outlet could reach 190°C. In such situations, it has become necessary to cool the gases before treatment by HF adsorption on alumina in order to protect the filtration media and to improve the overall scrubbing performance of fluorides. Several technologies have been developed and applied in recent years: dilution air cooling, water atomization in the upstream ducts and heat exchangers. The paper will present a technical and economical comparison of the various gas cooling technologies.

Introduction

The electrolysis of alumina to produce aluminum is a highly energy intensive process in which nearly half (7 kWh/kg) of the energy is lost as heat [1]. While most of the heat losses through each pot shell are as radiated heat, approximately 35% (2.45 kWh/kg) are contained in the pot exhaust flows that are channeled to the gas treatment center.

In recent years, the aluminum industry has seen its production shifting from northern countries to the GCC countries where energy is abundant and affordable. Also a significant number of plants boosted their production capacity by implementing pot amperage creep programs. Both of these developments have generally led to increase the gas temperature at the gas treatment center. The higher ambient temperatures and the lower specific pot exhaust rates have both led to an increase of gas temperature. Furthermore several authors have demonstrated that fluoride emissions increase with higher gas temperature (Ref. 2).

To improve the plant environmental performance through a better operation of the gas treatment centers and, in some cases to possibly reduce the carbon footprint of the aluminum smelter, some temperature control mechanisms, heat dissipation and/or heat recovery units have to be implemented. This paper intends to describe and compare the different approaches of pot gas cooling currently available or that are under intensive development.

1. Pot gas cooling technologies

The implementation of high amperage pot technologies (+ 300kA) and the construction of smelters in hot climate areas has led in some case to pot gas temperature in the range of 170 to 180°C that exceeds the maximum temperature of polyester felt media commonly used for filter bags in GTCs. Polyester felt has a temperature limitation of 140° – 145° C. The high cost of alternative media (Aramid felt that resists 200°C is 3 to 4 times the price of polyester) combined with the increase in fluoride gas emission at high temperature (see graph below [2]) favor the implementation of temperature control technologies upstream of the GTC. Although dilution air has been often used to control the seasonal excursions (pot gas temperature varies with ambient air temperature), a number of other approaches are now being tested and used providing a range of available options.

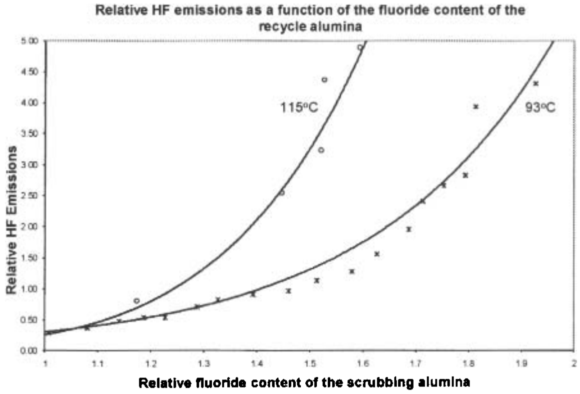

Figure 1 Relationship between HF Emissions and gas temperatures (from [2])

1.1. Dilution using ambient air

Dilution air is the simplest method to control GTC inlet gas temperature and has been installed on most systems engineered over the last 30 years. Modulating dilution air dampers are provided on the main ductwork approximately 20m upstream of the GTC inlet to allow sufficient distance to cool the process gas (from the pots) by mixing with ambient air. The mass of dilution air can be approximated from the following equation:

$$\dot{Q}_{DIL} = \frac{\dot{Q}_{IN} \times (T_{IN} - T_{OUT})}{(T_{OUT} - T_{AMB})}$$

Where

$\dot{Q}_{DIL}$ = Dilution flow in normal conditions $\left[\mathrm{Nm^3}/_{\mathrm{h}}\right]$
$\dot{Q}_{IN}$ = Air volume from the electrolysis pots $\left[\mathrm{Nm^3}/_{\mathrm{h}}\right]$
T_{IN} = Temperature from the electrolysis pots[°C]
T_{AMB} = Ambient temperature[°C]
T_{OUT} = Resulting temperature at the GTC inlet[°C]

In temperate climate countries, the dilution air requirement can easily be approximated as follows: each temperature drop of 10°C is equivalent to a 10% pot gas volume increase at the GTC inlet.

In order to keep constant flow at the pots to maintain the pot thermal balance and to ensure that there is no increase in potroom roof emissions, the GTC must be enlarged to allow for the increase in total gas volume to be treated. Process flow measurements upstream of the dilution air dampers are then required to control the operation of the GTC induced draft fans. In order to limit the size of the GTC, dilution is usually best suited for a temperature drop of 5 ° to 15°C.

This cooling method has however a negative impact on the overall GTC power consumption. Because of the requirement to maintain constant gas volume at the pots when dilution air is activated, the GTC fan power increases proportionally with the % of dilution air when activated. If dilution air is used only a few hours or days per year, the impact is marginal although over sizing the fans reduces the fan performance efficiency and its associated power consumption by +/- 3% when operating in normal mode – without dilution air. If the dilution air mechanism needs to be activated for long period (months), it is probably best to consider its implementation in combination with other gas cooling methods.

On the positive side, as dilution air systems are generally used periodically, the GTC system greatly benefits the remainder of the year from the included additional filtration area. A lower filtration velocity operation ensures lower dust emissions, reduced fan power consumption and lesser compressed air usage which all have positive effects on bag lives and their associated maintenance costs.

1.2. Hairpin coolers

A significant quantity of gas cooling is normally achieved by convection losses of the ductwork surfaces between the pots and the centralized GTC. A modern potline has up to 1400 meters of un-insulated duct upstream each of its two GTCs; this typically allows for a 15 to 20°C temperature drop. A recent innovation developed by Solios (Patent Pending [3]) to further reduce the GTC inlet gas temperature is to install at each pot a vertical hairpin cooler which increases the exchange surface between the ambient air and the pot gases. The hairpin cooler is installed where the gas temperature is the highest and makes it possible to drop the temperature upstream the GTC by another 10°C, hence reducing the need for dilution air and its impact on the sizing of the GTC.

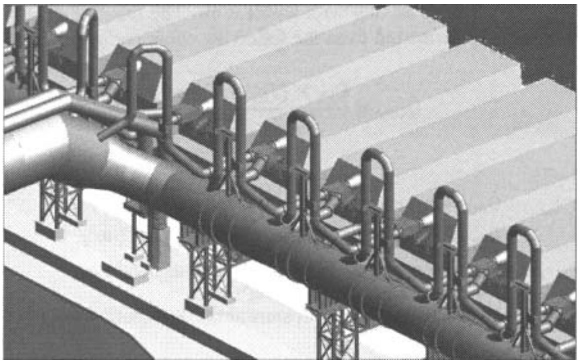

Figure 2: 3D model of hairpin coolers - system presently under construction in the GCC

Although the cooling gained by this technique is limited, it has the benefits of simplicity without the need for any new mechanical equipment. It is also beneficial to help balance the flow at each pot and its impact on the temperature reduction is gained all year around. Its installation has no incidence on the GTC power consumption since the hairpin cooler pressure loss is rather low and is fully compensated by the reduction of actual volume handled by the GTC fans.

1.3. Water spray cooling

Another method to reduce the GTC inlet temperature is based on the installation of spray lances to finely atomize water droplets in the upstream ductwork [4]. The evaporation of water is endothermic and is an efficient way to cool hot gas streams. Until quite recently, spraying water inside potline ductwork was considered too risky in regards to the potential for scaling or corrosion if water droplets were to come in contact with the ductwork walls. This system, which is patented by RioTintoAlcan, is at the moment implemented at two smelters for seasonal uses: Tomago Aluminium (Australia-2003) and Sohar Aluminium (Oman-2011). The large diameter of upstream ducts (3.5 to 5 meters) coupled to the advance in dual fluid water atomization and to the effective use of computational fluid dynamic (CFD) to study gas flow patterns upstream and downstream of the spray lances have allowed this technology to be implemented successfully.

There are two essential operating parameters for a spray system to work well:

- The water flow
- The compressed air flow

The water flow controls directly the temperature drop of the gases. It is expressed by the following formula

$$\dot{Q}_{H2O} = \frac{\dot{Q}_{IN} \times CP_{Gas} \times (T_{IN} - T_{OUT})}{\lambda_v + \left[CP_{H2O,l} \times (100 - 20) + CP_{H2O,g} \times (T_{OUT} - 100)\right]}$$

Where

Q_{H2O} = Quantity of water required to cool the gases $\left[{}^{kg}/_{h}\right]$
$\dot{Q}_{IN}$ = Air volume from the electrolysis pots $\left[{}^{kg}/_{h}\right]$
T_{IN} = Temperature from the electrolysis pots[°C]
T_{OUT} = Resulting temperature at the GTC inlet[°C]
$CP_{H2O,l}$ = Heat capacity of the water in the liquid state $\left[\frac{kcal}{kg°C}\right]$
$CP_{H2O,g}$ = Heat capacity of the water in the vapour state $\left[\frac{kcal}{kg°C}\right]$
λ_v = Latent heat of vaporization of the water $\left[\frac{kcal}{kg°C}\right]$

The water droplet size distribution has a direct impact on the evaporation time. It is essential for the water evaporation to be complete prior to getting into the alumina dry scrubber to avoid any possible corrosion hazards. The larger the droplets, the longer are the evaporation times. Considering the rather short length of duct available on most of the installations (15 to 30 m), the total evaporation time available is limited to only 0.75 to 1.5 seconds.

It is therefore mandatory to produce very small droplets not exceeding 100 microns diameter, which can only be produced by dual fluid nozzles using large quantity of compressed air.

This method is efficiently used to drop gas temperature by 10° to 30°C but the gas temperature shall not be lower than 135°C as the residence time and straight duct sections commonly available downstream of the water atomization location points are not sufficient to achieve lower temperatures. Safety and complementary cooling with dilution air is required downstream to ensure continuous service as required for all GTCs.

Industrial implementations of this technology have demonstrated satisfying results in regards to gas cooling, scale build-ups, hydrolysis of the polyester fabrics and corrosion risks provided locations, design guidelines for the insertion of the spraying ramps and for automation are strictly respected.

1.4. Heat exchanger cooling

The use of indirect gas to water heat exchangers to cool the gases offers the benefit of very effective cooling with capability to reduce the GTC inlet temperature by 40°C. However such technology adds additional equipment (pumps, water piping and water circuit heat exchanger) that needs to be evaluated in terms of maintenance. Furthermore, the heat exchanger design must be adapted for the specific characteristics of the potline gases: dust abrasiveness and fouling of the tubes with scale formation. It is also necessary to consider that the equipment will sometimes require bypass or be of a modular concept to allow inspection and maintenance while maintaining the GTC in continuous operation.

Two types of heat exchangers are available: the fire tube design where gases circulate inside the tubes with water on the outside (Figure 3) and the shell and tube design with water circulating inside the small pipes installed perpendicular to the flow of the hot gases. The shell and tube design is much more compact and efficient in terms of heat transfer and less costly to build (no need for a tight pressurized water casing). Fins can also be added to the outside of the tubes to increase the thermal exchange. Considering the very large gas volume to be cooled, this technology is more advantageous.

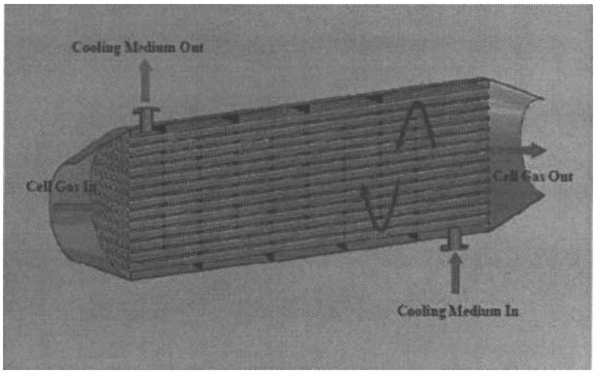

Figure 3: Shell and tube heat exchanger with gas flowing inside the tubes

One concern of the shell and tube technology has been the build-up of scales on the surfaces of the tubes. Tests done a few years ago by the Hamburg University at the Hamburg Aluminum plant in Germany had shown rapid fouling of the heat exchanger tubes (Figure 4).

Solios is presently participating to a research program on a smelter site in collaboration with Hydro and NTNU – Norwegian University of Science and Technology that is aimed at testing a heat exchanger with specially shaped fin tubes to minimize build-up in order to assess long term performance and maintenance requirements.

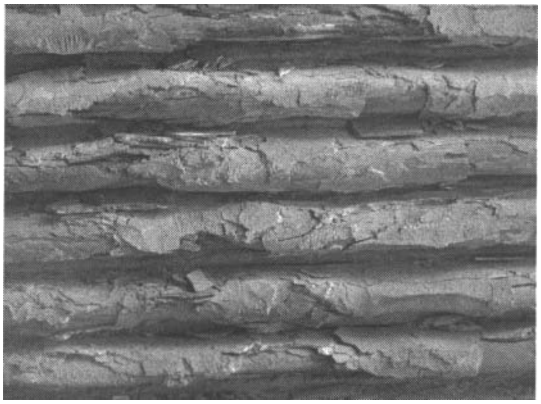

Figure 4: Build-up on the first row of tubes in the heat exchanger [5]

Preliminary studies have shown that the best configuration is to use 4 to 8 heat exchangers in a typical pot gas scrubber configuration. The heat exchanger gas side pressure loss to be taken into consideration in the analysis of different solutions should be in the range of 40 to 60 mmW.G.

Energy withdrawn from the process could be either dumped to the ambient or more preferably recovered. Depending on the geographic location of the site and of the local needs, the recovered energy could be used for different uses, such as:

- District heating and agricultural uses;
- Air conditioning;
- Water reheating in desalination plants or in power generation plants; and for
- Electricity generation thought the use of a Kalina or an ORC cycle.

2. Analysis of the different pot gas cooling technologies

The selection of a proper cooling strategy for a specific site is not universal; it requires a multi-dimensional analysis and shall answer to the following:

a. What is the level of cooling required to either cooling the gases to a temperature level that is compatible with the filtering material installed in the alumina dry scrubbers or to a temperature that will provide adequate level of fluoride adsorption efficiency?

b. What are the relative investment costs (CAPEX) and operating costs (OPEX) associated with the strategy? Is the solution compatible with the existing installation or with the proposed layouts?

In the following subsections, we briefly present the relative capital cost investment required for the implementation of each technology in proportion to the cost of a Gas Treatment Center itself, an evaluation of the operating costs of each technology and, finally, develop a table summarizing the pros & cons and main characteristics of each identified cooling option.

2.1. Relative capital cost investment of pot gas cooling strategies

Based on Solios' experience in engineering and delivering GTCs and their associated components, we have the following relative capital cost indexes.

Complete GTC c/w main ID fans, discharge stack, upstream ducting and all internal alumina handling equipment	100
YPRIOS Dual Draft ventilation system c/w interconnecting ductwork and booster fans	12
Hair pin cooler ducts installed on each pot for a 10°C temperature drop	3.2
Water spray cooling equipment and controls including air compressors - cooling of up to 30°C	6.5
Heat exchanger system c/w dump heat system – cooling of up to 40°C	15
Dilution air cooling for a 10°C temperature drop complete with the increase in capacity of the GTC	5.5
Dilution air cooling for a 20°C temperature drop complete with the increase in capacity of the GTC	11.0
Dilution air cooling for a 30°C temperature drop complete with the increase in capacity of the GTC	16.5

The different pot gas cooling technologies can be implemented at capital costs representing 3.2 to 16.5% of the costs of a standard GTC.

2.2. Evaluation of operating costs of various solutions

The comparison of different gas cooling solutions in terms of operating costs can be done by comparing the power cost and the water usage cost. Please note that we haven't included any maintenance and repair cost in the operating costs which, in some cases, could potentially represent 5 to 9% of the fixed capital investment on an annual basis [6].

The following has been taken into consideration when comparing each solution with the base case where the GTC is designed for a gas temperature not exceeding 135°C (temperate climate smelter site):

- Dilution air cooling adds to the total volume treated and to the ID fan power consumption in the same proportion of the following temperature ratio:

$$[(T_{IN} - T_{OUT}) / (T_{OUT} - T_{AMB})] + 1$$

- Hairpin coolers add approximately 0.2 kPa or 4% to the system pressure losses and fan power.
- Spray cooling doesn't add to the GTC fan power but requires more compressed air power for atomization. It also consumes fresh water which is costly if produced from a desalination plant (typically \$2.50/m^3 in GCC countries).
- Heat exchangers add system pressure losses (between 0.4 kPa to 1 kPa depending of the HE design) representing between 8% and 20% of extra fan power.
- Heat exchangers used for heat dissipation also need auxiliary power to run the water pumps and the axial fans of the dump heat water cooler circuit. Typically this will represent an equivalent between 5% and 10% of the GTC ID fan power consumption.

The relative OPEX of the various solutions are shown in the table below. Water usage cost of \$2.50USD/m^3 is compared to power cost valued at \$0.04USD per kWh.

		Climate	
		Temperate 25° C- 40°C	*Tropical* 45°C-55°C
Impact on exhaust fan consumption	**Maximum temperature drop required at GTC**	**20°C**	**40°C**
	1. Dilution only	Flow: +20%	Flow: +50%
	2. Hairpin + dilution	Flow: +10% ΔP: +4%	Flow: +38% ΔP +4%
	3. Heat exchanger	ΔP: +12%	ΔP: +18%
	4. Spray cooling	No impact	No impact
Impact on OPEX	**Base GTC fan power relative cost**	**100**	-
	1. Dilution only	+20	+50
	2. Hairpin +Dilution	+14	+44
	3. Heat exchanger and dump heat system	+16	+28
	4. Spray cooling:		
	a. Compressor costs	+8	+15
	b. Water usage costs based on \$2.50 per m^3	+18	+36

3. Cooling technologies summary table

The following table summarizes the characteristics and pros & cons of each of the different available approaches.

Cooling technology	Cooling capacity	Pros	Cons	Preferred application
Dilution air	Ideal for 5° to 15°C cooling.	✓ Easy to implement. ✓ Does not add new type of equipment ✓ Proven and low-risk solution	✓ Not ideal for large temperature drop (≥20C). ✓ Increases size of GTC. ✓ Increase in power costs (ID Fans) when dilution is used for long periods. ✓ Increase total installed power	✓ Smelters located in moderate climate with maximum ambient temperature of +/- 35°C. ✓ Frequencies of warm temperatures of +/-3 months out of 12.
Water spray cooling	10°C to 30°C with minimum temperature of 135°C after evaporation	✓ Does not increase the GTC size.	✓ Potential risks of corrosion and scales. Required reliable instrumentation and good maintenance practices. ✓ Fresh water consumption ✓ Important compressed air consumption.	✓ Retrofit on existing GTCs possible if upstream duct configurations allow. ✓ Where continuous operation is not required and dilution air can be used as back-up during cold season.
Heat exchangers	25°C to 40°C	✓ Does not increase the scrubber size. ✓ Lowest OPEX solution (without maintenance and repair costs) for hot climate for temperature drops greater than 25°C. ✓ Can lower GTC inlet temperature to 110°C for better fluoride gas capture.	✓ By-pass or modular concept design required and tube fouling to be monitored. ✓ Add many new equipment that will add to maintenance work. ✓ CAPEX is high for applications where limited cooling is required (ex: 5-15°C)	✓ Smelters in hot climate with gas cooling required at least 6 to 8 months per year. ✓ Ambient temperature of 30°C to 55°C
Hairpin coolers	10°C	✓ Simple ✓ No water required ✓ No incidence on fan power ✓ Can be used in combination with dilution cooling. ✓ Low maintenance ✓ Low-risk solution	✓ Limited cooling capacity.	✓ Future plants in hot climates with limited water supply. (in combination with dilution air)

Conclusion

The selection of a pot gas cooling strategy for a specific location cannot be made using a simple equation but it can be made by looking at the plant requirements and global objectives.

For example, Figure 5 illustrates what would be the average monthly temperatures entering a GTC if no additional cooling method other than the convective heat losses from the upstream ducting was considered.

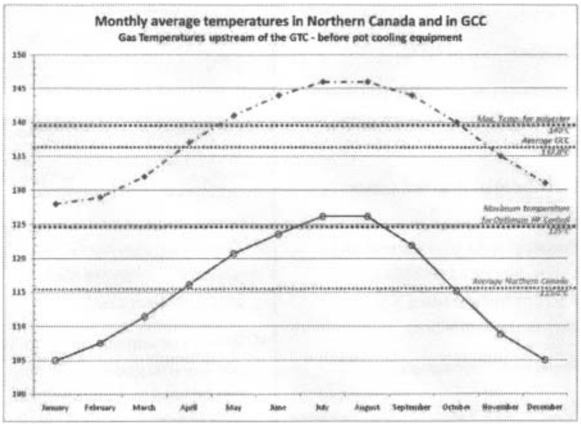

Figure 5 Graph illustrating seasonal variability of the gas temperature at the GTC inlet

Plants located in temperate climate countries would not typically require pot gas cooling system other than to cope for the maximum peak temperatures which are typically 10°C higher than average ambient temperature and occurring only several days per year. These plants would benefit from the simple air dilution systems that are commonly considered to protect the filtration bags against abnormal temperature excursions.

On the other hand, plants located in hot climate countries such as GCC countries are facing a much different situation as the normal average ambient temperatures and associated GTC inlet temperatures are significantly greater, thus approaching the maximum temperature under which the polyester filtration media can operate without significant deterioration and exceeding nearly at all time 125°C which is generally recognized as the temperature at which fluoride emissions tend to degrade. Combining simple cooling mechanisms such as the simple hairpin heat exchangers and the conventional air dilution systems represent a relative low-cost and low maintenance solution. This selection would also ensure that the GTCs operate in a comfortable zone with low operating and maintenance costs while still providing excellent fluoride capture efficiencies. When these cooling mechanisms are coupled to dual draft ventilation systems [7] that are nowadays more and more implemented to minimize release of contaminants during pot maintenance work, the total fluoride emissions of the plants is guaranteed to be optimal.

The recent installation of water spray cooling systems by Solios at Sohar Aluminium should allow, in the next 6 to 12 months, to better assess the real potential of this solution in the GCC.

Long term reliability of other type of heat exchangers still need to be demonstrated as the fouling of the heat transfer surfaces with hard gray scales has thoroughly been discussed and identified as the main challenge in the development of workable and reliable solutions. Solios is presently involved in on-going research work on this subject pilot-testing a promising configuration of heat exchangers which should enable also to conclude on the non-fouling risk and on the full potential of this technology.

Finally, heat recovery for power generation remains an ideal goal for the aluminum producers to help in reducing the operation costs and the smelter's carbon footprint. Unfortunately, the production of electricity remains difficult due to the fact that temperatures evolving from the electrolysis cells off-gases are too low to allow an efficient use of existing recovery technologies.

References

1- K. Grjotheim, B. J. Welch, Aluminium Smelter Technology. A Pure and Applied Approach, Aluminium-Verlag Düsseldorf, 1980

2- H. Vendette, N. Dando, A. Moras, E. Marion and W. Xu, “Alumina Dry-Scrubbing Technology: Development of a Cascade Feeding System for Improved Capture Efficiencies”, Light Metals 2007, The Minerals, Metals & Materials Society, pp. 187-191.

3- T. Malard, E. Bouhabila, “Device for Collecting Gases Emitted by Aluminum Electrolysis Cells and Associated Aluminum Production System” Solios Patent N° FR2948128-2009.

4- M. Bonnier, S. Massambi, J-M. Jolas, G. Girault, V. Demetriou, D. Wheaton “Development of a System Based on Water Atomization to Decrease, Prior to Treatment, the Temperature of the Gas Emitted from Aluminum Cells” Light Metals 2007, The Minerals, Metals & Materials Society, pp. 193-197.

5- J. Eiden, C.N. Rangong, J. Hapke. E. Sturm. 2003 “Experimental and Theoretical Investigations of a Pilot Heat Exchanger for Heat Recovery at the Hamburger Aluminium Werk GmbH.” Proc. Fourth Int. Conf. on Compact Heat Exchangers and Enhancement Technology for the Process Industries. Technical univ. Hamburg. Hamburger Aluminium Werk Gmbh.

6- M. S. Peters, K. D. Timmerhaus, Plant Design and Economics for Chemical Engineers, 4th Edition, 1991, McGraw Hill

7- T. Malard, M. Depinoy, “ALBA Line 5 Expansion - Solutions for a Better Environment”, Light Metals 2008, The Minerals, Metals & Materials Society, pp. 389-393.