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ALUMINUM REDUCTION TECHNOLOGY

Equipment

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INTEGRATED DESALINATION AND PRIMARY ALUMINIUM PRODUCTION

Anders Kenneth Sorhuus 1), Geir Wedde1), Dario Breschi2), Nolwenn Favel3), Guillaume Girault3)

1) Alstom Norway AS - Drammensveien 165 - 0277 Oslo - Norway

2) Alstom Power Systems SA- Building 329 - 1 rue Alice et Paul Kroner - 90300 Cravanche - France.

3) Rio Tinto Alcan - LRF – BP114 – 73300 St Jean de Maurienne - France

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Abstract

Primary aluminium is produced increasingly in regions where there is a scarce supply of clean and fresh water. A self sustainable, secure supply of fresh water is of strategic importance for aluminum smelters. Desalination plants can be installed in combination with gas-fired power plants, and it is shown that part of the natural gas consumed for production of water in the desalination process can be replaced with waste heat from the aluminium smelter pot gas. Besides, installation of heat exchangers allows a significant downsizing of Gas Treatment Centers as well as improved control of stack fluoride emissions. It is shown that a compact, robust double-effect desalination plant can provide the water required during predicted variations in water consumption and profitably use wasted heat for a typical AP40 smelter. The corresponding calculated cost of water is comparable to the cost of water available commercially.

Introduction

Aluminium smelters consume significant amounts of fresh water, which is mainly used in the different processes as a cooling agent. As illustrated in Figure 1, main consumers include the casthouse assuming ingots are produced, the carbon plant, and the compressors supplying compressed air to the smelter as a whole.

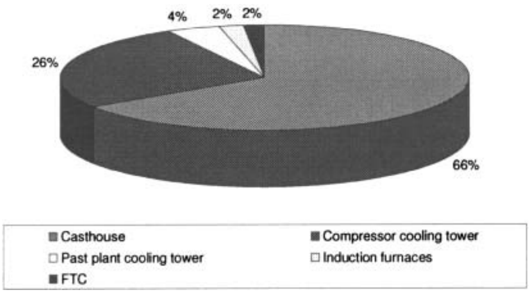

Figure 1 – Main fresh water consumers from one typical modern Middle-Eastern smelter

In recent years, significant reductions in water consumption have been achieved, mainly through the use of more efficient cooling processes [1]. A modern smelter now typically consumes less than 10m^3/tAl, and figures lower than 1m^3/tAl have been reported by some Rio Tinto Alcan smelters.
Aluminium production increasingly tends to be located in hot countries. The Gulf Cooperation Council (GCC) share of the world aluminium production capacity is, for instance, projected to reach close to 14% by 2014 [2], up from less than 5% in 2000.

In these countries, access to a secure fresh water supply source is often limited. When a smelter relies on its own power plant for electricity supply, as is frequently the case in the Middle East, the required water flow can be provided by a desalination unit combined with the same power plant. This is, for example, the case of the Sohar Aluminium smelter. This possibility is increasingly considered for new greenfield projects.

This option, using some of the low-grade heat produced by the power plant, is significantly more energy-efficient compared to the solution consisting of a dedicated boiler supplying the desalination unit. However, the water production process still induces additional energy consumption. This is due to the fact that the low-pressure steam extracted at typically 100°C from the power plant and used for water desalination could instead be utilized to produce more electricity from the turbine.

The maximum additional power that can be produced can be estimated from a Carnot cycle analysis. Assuming that approximately 50% of the Carnot cycle efficiency can be obtained, and that the normal power plant condenser temperature is at 50°C, the electric power that can be produced from the 100°C low pressure steam is in the range of 5-10% of the thermal energy of the extracted low pressure steam. With waste heat potentials from the pot gas in the range of 10-20% of the electric energy consumption for the aluminium smelter, 1-2% reductions in the specific energy consumption for the aluminium production can be calculated by replacing the extracted low pressure steam with waste heat from the pot gas.

Another characteristic of smelters located in hot countries is that they typically face high levels of pot gas temperatures, which can be detrimental to Gas Treatment Centre (GTC) operation [3]. In this context, Alstom has recently developed a range of pot gas heat exchanger (HEX) technologies, which ensure the GTC is continuously operated at its optimum gas temperature – typically less than 120°C.

Since it allows a significant reduction in GTC size, and despite the additional investment incurred by these heat exchangers, the overall cost of this design, including HEX, is cost competitive. As a by-product of HEX operation, a large amount of free low-grade heat is then made available in the form of hot water.
The opportunity of using this heat to produce fresh water in a dedicated desalination unit is discussed in this paper.

Pot gas heat valorization

Case study description

The discussion will be based on a hypothetical AP40 [7] smelter located in a Middle-Eastern country.
The smelter includes one potline (360 pots) operating at 400kA and producing 403ktAl/year. Two GTCs are installed, each servicing half of the pots and equipped with 24 Alstom Abart filters with integrated heat exchangers. Plant fresh water consumption is assumed to be 403,000m^3/year. Table 1 summarizes the main technical parameters used as an input for the case study.

Item	Unit	Value
Pot amperage	kA	400
Number of pots / potline	-	360
Pot flow rate	Nm^3/s	2.60
Max. ambient temperature	°C	50
Min. ambient temperature	°C	15
Max. temperature downstream HEX	°C	<115
Smelter water consumption	m^3/year	403,000

Table 1 – Main technical parameters used as the basis for the case study

Pot gas heat characteristics

Pot gas heat accounts for a large percentage of the total energy dissipated by the pot, typically more than 30%. This heat can in turn be estimated on the basis of pot gas flow rate and temperature, using the following formula: $P_{total} = Q.C_{P}.(T_{pot}-T_{amb})$, where Q is the pot gas flow (in kg/s), T_{pot} and T_{amb} the gas and ambient temperatures, respectively, (in °C); and C_p the gas heat capacity (in kJ/(kg.K)). For AP40 cells operating at 400kA, this would correspond to approximately 380kW/pot, or 137MW per potline.

Assuming a heat exchanger is installed upstream from the GTC inlet, and that it maintains gas temperature at a constant value of say 115°C, the previous equation can be rewritten as follows:

$$P_{total}=Q.C_{P}.[(T_{pot}-T_{GTC})+(T_{GTC}-115)+(115-T_{amb})]=E_P+E_R+E_L$$

where T_{GTC} is the temperature at the GTC inlet. The term $Q.C_{P}.(T_{GTC}-115)$ (E_R) represents the fraction of pot gas energy which is recovered. It depends on the gas temperature, and therefore on the ambient conditions: more heat will be available in summer when ambient and therefore gas temperatures are higher. On the other hand, no heat is recovered when the GTC inlet temperature is below 115°C. The term $Q.C_{P}.(T_{pot}-T_{GTC})$ (E_P) corresponds to the heat dissipated in the ductwork between the pot outlet and the GTC inlet. Finally, $Q.C_{P}.(115-T_{amb})$ (E_L) corresponds to the heat that will be dissipated within the GTC and at the stack.

Figure 2 shows how E_R is expected to evolve under different ambient conditions, based on simplifying assumptions (constant temperature differences $T_{pot}-T_{GTC}$ and $T_{pot}-T_{amb}$). The ambient temperatures used to build this graph correspond to the daily averages between 1997 and 2004 in Sohar (Oman).

On this basis, up to 20% of the pot gas heat daily average is recoverable in summer. The yearly average would be close to 10%. This percentage can be increased by reducing ductwork losses (E_P=13% in our example), for example by installing the HEX as close as possible to the pot outlet. Another solution consists in reducing the heat exchanger setpoint. In any case, minimum heat exchanger surface temperature should be well above the expected minimum SO_3 dew point limit to avoid potential corrosion problems.

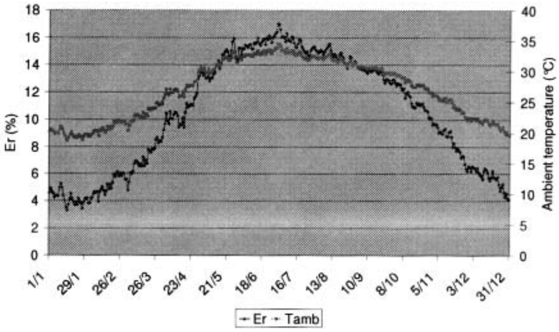

Figure 2 – Recoverable heat in pot gas versus ambient temperature

Pot gas heat valorization

Valorization of the heat captured from pot gases has been a recent subject of interest [3, 4, 5]. The main limitations of this valorization include the poor quality of the available heat (gas temperature is typically below 150°C) and the fact that it fluctuates according to ambient conditions, as discussed above.

The other criteria that can be used when assessing different valorization options include:

- Their economic evaluation
- Their technical maturity
- Their compliance with regulatory and political constraints
- Their overall environmental benefit (if any – in addition to energy consumption reduction, which is the primary objective of heat valorization)
- Whether energy is reutilized internally in the smelter – internal utilization is preferred since it is usually easier to implement
- Whether a significant percentage of the total recoverable energy can be valorized

The main families of solutions that have been explored to date include production of electricity, for example through the use of Organic Rankine Cycle (ORC) machines. Based on internal assessments, the current level of efficiency of these technologies makes this solution economically challenging at this stage. Active R&D is, however, being currently conducted in this domain, which could change this assessment in the near future.

District (and/or plant) heating is operational in a few smelters, for example in Norway, but is of course not applicable to hot countries. It still remains one of the best options for cold climates. Alternatively, heat could be used to supply energy to air conditioning units through absorption cycles. In both cases, the energy might not be valorized for part of the year.

The third solution which consists in valorizing heat in a desalination plant to produce fresh water appears particularly relevant compared to the previous alternatives, based on the criteria listed above. Indeed, it would use a mature technology (desalination), which has already been successfully implemented throughout the world. As will be shown, a sizeable share of the available energy could be used, and the demand is present both in summer and winter. Finally, this option reduces the environmental footprint of the smelter by minimizing its reliance on external fresh water sources.

This solution was therefore prioritized for further investigation, in order to understand its limitations and evaluate its economical value.

Heat valorization process description

Overall process description

The proposed process for pot gas heat valorization is illustrated in Figure 3. The desalination plant energy required for its operation is provided by extracting heat from the hot pot gas. Water is used in a closed-loop circuit to convey energy from the HEX to the desalination plant. Fresh water is produced from seawater, based on a process that will be discussed in the next section.

Two options are available for sizing the desalination plant. In the first case, it can be sized simply to supply the smelter with its required fresh water needs. In this case, as will be seen, not all the available heat would be valorized. Alternatively, a larger desalination plant could be built, with the goal of valorizing close to all of pot gas recoverable heat. In this case, fresh water could be sold to external clients. As already discussed, internal solutions are preferred at this stage, and this study is therefore focused on the first option (in-house utilization).

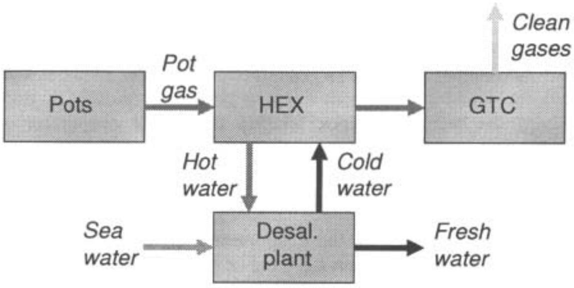

Figure 3 – Overall simplified process proposed for pot gas heat valorization

Heat exchanger

The location of the HEX upstream from the GTC offers additional benefits such as reduction in size, operating cost and HF emissions of GTCs, but, on the other hand, means that the heat transfer surfaces are exposed to dirty, scaling pot gases. Extremely robust heat exchangers of shell and tube design are therefore used. In these heat exchangers, the dirty pot gas flows in side straight tubes that minimize the risk of impact induced scaling and deposits. These heat exchangers are specifically designed for this application.

As shown in Figure 4, the pot gas flows inside the straight HEX tubes parallel to the heat exchanger surfaces to minimize scaling by impact. The only point of impact is at the entrance to the tubes, which is formed in a patent filed trumpet shape to ensure low gas/scaling velocities during acceleration of the gas at the entrance. Clean deoxidized water enters the heat exchanger on the shell side, and flows on the outside of the heat exchanger tubes.

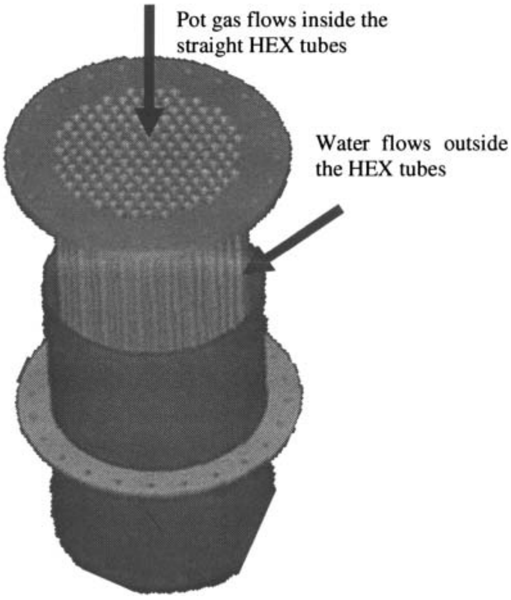

Figure 4 – The pot gas "shell –and –tube" heat exchanger

Continuous development of and improvements to the HEX technology over several years have accumulated a robust and mature basis for evaluation of heat transfer, the degree of deposits on the heat transfer surfaces, and corrosion. R&D has resulted in several improvements including integration of the heat exchanger into the GTCs (iHEX), see Figure 5.

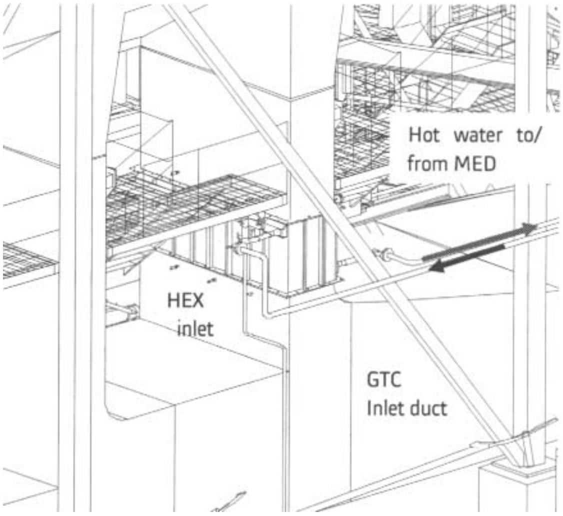

Figure 5 – The integrated Heat Exchanger (iHEX).

As shown in Figure 5, one iHEX is located in each reactor upstream from the individual GTC compartments, offering the following main characteristics:

- Stable gas flow and temperatures independent of ambient conditions
- Improved balance of gas between compartments, and gas distribution inside the reactor
- Improved efficiency on HF scrubbing
- Smaller footprint (fewer compartments)
- Increased robustness for alumina fall out in the reactor
- Recovery of energy – e.g. 1 MW per unit
- Excellent access from outside due to the relatively small size and rectangular shape of iHEX
- Built in N-1 redundancy since one compartment can be off line.

Desalination Plant Description

In our feasibility study, selection of the technology for the desalination plant and the assessment of its most suitable integration into the gas cooling system of the aluminium smelter have been based on the following constraints:

- Availability of the heat recovered from the HEX in the 28 to 41 MW range, in the form of hot water in closed circuit, the delivery temperature of which fluctuates according to HEX operation;
- Avoidance of any availability reduction in the HEX cooling system due to operation of the desalination plant;
- The total amount of water consumed by the smelter for its own operation is 403,000 m³/y, corresponding to approximately 1,200 m³/day to be provided continuously throughout the year;
- The cost of water produced by the integrated solution shall be competitive with respect to alternative solutions for its provision.

Considering that in our specific application the recovered heat is available in the temperature range of 60°C to 90°C, selection of the Multi-Effect Distillation (MED) technology for seawater desalination appears the most suitable for the specific application. In fact, this distillation process allows efficient utilization of available heat at this low temperature level with the following additional advantages:

- Robust distillation technology, ensuring that plant operation is not affected by the quality of feed seawater (as could be the case for membrane-based processes);
- Minimum consumption of electrical energy for the auxiliaries of the desalination plant (around 0.5 kWh for each m³ of produced distillate, versus around 4 kWh/m³ in the case of Reverse Osmosis);
- Minimum cost for Operation and Maintenance (no dedicated staff required, no need for periodical membrane replacement);
- Reduced chemical consumption as compared to membrane processes;
- High purity of the produced distillate (residual salinity below 5 ppm), which makes it particularly suitable for process utilization.

MED technology, featuring horizontal tubes and thin film evaporators, currently boasts an extensive operation record in the seawater desalination industry, with a unit water production capacity ranging from 500 to 40,000 m³/day. A detailed technical description of the multi-effect process is not within the scope of this paper, and may be found, for instance, in the document [6] and in its bibliographical references. A picture of a MED installation is presented in Figure 6.

Figure 6 – A typical MED plant installation

The envisaged integration diagram between the pot gas heat exchangers and the MED desalination plant is presented in Figure 7. The pot gas flow is cooled down as it passes through the tube side of a battery of the above-described heat exchangers, located in the two Gas Treatment Centers of the smelter. The cooling medium (water) is correspondingly heated up in the shell side of the same exchangers, and circulated in a closed loop.

Two heat sinks are present in the same closed loop, namely a Steam Generator (kettle-type boiler) and a Dump Cooler (seawater-cooled exchanger). The former recovers sensible heat from the closed-circuit warm water to produce (typically by pool boiling) the saturated vapor feeding the MED evaporator at roughly 60°C (under vacuum conditions). In the MED evaporator, production of distillate occurs by a condensation / evaporation process repeated in each effect.

The number of effects in the evaporator may vary from one to more than ten, depending on the level of thermal efficiency that is specified for the system (the larger the number of effects, the greater the production for a given amount of heat input). The vapor produced in the last effect is finally discharged into an external condenser, cooled by seawater.

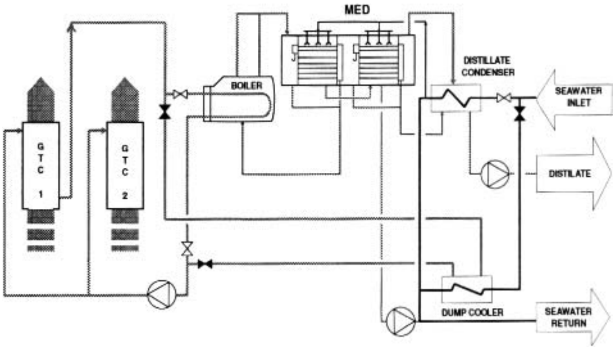

Figure 7 – HEX – MED interconnection diagram

The seawater-cooled exchanger installed in the same closed loop can operate parallel or alone, as it is sized to dump the maximum heat flux exchanged with the HEX. Its function is both to cover the peaks that cannot be handled by MED normal operation and to allow operation of the HEX even during MED outage periods.

Technical challenges – interfaces between the HEXs and the desalination units

Although design of a MED desalination plant is in itself a well–consolidated practice, application of this technology to the recovery of heat discharged by a flue gas cooler presents new problems in relation to proper integration of the two systems, in order to fully benefit from the availability of recovered heat. In particular:

- In standard MED projects, heat input is provided by steam in constant conditions. In our case, heat is made available to the MED unit in the form of warm water, with significant fluctuations in delivery temperature depending on ambient conditions and smelter operation. Conversely, the water production necessary for the smelter has to be assured continuously since water storage capacity is limited to a very few number of days.
- In the case considered here, operation of the MED plant will ensure that on no account the gas temperature at the HEXoutlet will exceed 115°C.
- The concept for interconnection between the various components will be sufficiently robust to assure that tripping of the MED unit will on no account affect operation of the smelter.
- Availability of the heat sink for HEX operations has to be complete.

The above challenges are met by the following design solutions:

- Adoption of a tube-bundle, kettle-type evaporator at the interface between the closed-loop water circuit and the MED circuit, ensuring hydraulic separation between them.
- Installation of a Dump Cooler in the closed-loop circuit, in parallel to the MED.
- Coordinate control of the HEX, MED and Dump Cooler, in order to guarantee the most efficient and safe operating conditions at all times

Based on these conditions, simple steady state calculations of annual fluctuations in gas temperatures and water production have been performed as shown in Figure 8. In this calculation, heat transfer fluid flow , pot gas flow, and the sea water temperature have been kept constant. The only variable is inlet pot gas temperature at the HEX inlet (T_{HEX1}):

$$T_{HEX1} = T_{Amb} + 105\ °C.$$

This relationship, familiar from previous experience with AP40 pots, is reasonable considering that heat generation in pots is more or less independent from ambient conditions as long as gas flow is constant. The annual variation in pot gas temperatures in and out of the HEX (THEX1 and THEX2) corresponding to the expected maximum and minimum ambient annual temperatures (T_{Amb}), and the predicted water production for the MED under these conditions are shown in Figure 8.

Heat exchanger size is optimized to provide the required cooling for the GTC, and, as shown, provide sufficient heating of the proposed double-effect MED system. In this case, the model predicts higher water production than required over the summer period. To reduce this unnecessary water production more heat can simply be dumped in the seawater dump cooler.

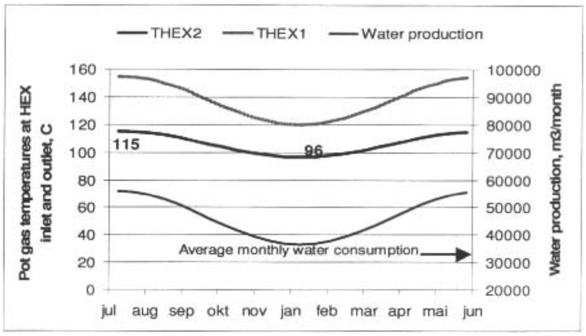

Figure 8 – Annual predicted variations in pot gas temperatures and MED performance.

Business case

Two size MEDs are explored. The smaller size MED is compatible with the predicted consumption of our hypothetical aluminium smelter of 403,000m^3/year, and the larger "commercial size" MED is capable of producing 1.7 million m^3 /year. The cost of water is calculated in both cases, and compared to the cost of water produced from similar size MEDs which would be combined with a gas fired power plant associated with the smelter. The typical procured cost of water from an external source will also be used as another reference.

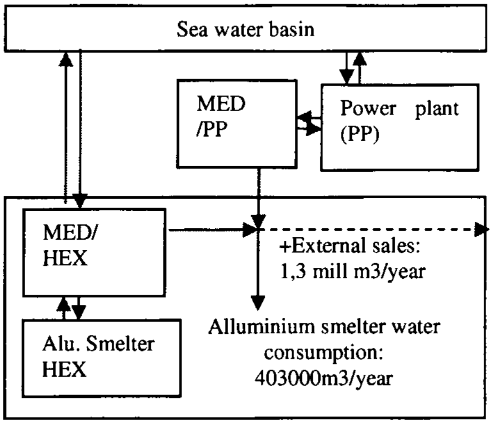

Figure 9 – MED integrated with aluminium or a power plant

In order to calculate the cost of water produced from the various options, a number of commercial and technical assumptions are made. Technically, it is assumed that the same size MED is required to produce the same amount of water either by using waste heat from the pot gas, or by extracting low pressure steam from the power plant.

In both cases a similar amount of piping is needed to connect to the seawater basin, the pot gas heat exchanger system, or the power plant low pressure steam extraction system, as indicated in Figure 9 with the blue and red arrows indicating to and from pipelines for water or steam, and with the length of the arrows indicating the relative length of the pipelines. The pot gas heat exchangers, the seawater cooled dump heat exchanger, and the associated piping, are included in the GTC investment costs as the calculated benefits (e.g. reduced GTC size), which, in any case, more than outweighs the cost of this equipment.

The capital cost of the MED unit and associated piping is therefore similar in both cases, the only difference being that the waste heat from the pot gas is free, whereas the extraction of low pressure steam on the power plant reduces power production by a marginal amount, calculated based on an overall energy balance of a combined cycle power plant. The main result of this calculation is that the cost of low pressure steam is approximately 2 USD/ton Al. One main assumption in this calculation is the cost of fuel (gas) of 1.7 USD/Gjoule.

The calculated water cost is shown in Figure 10. This cost is based on historical cost estimation data that have been validated via updated technical and commercial quotations from MEDs. The investment cost dominates in most of the cases the cost of water as shown in Figure 10. In the calculations, a lifetime for the MED plant of 25 years and an interest rate of 6% have been used.

As shown in Figure 10, it is possible to produce water at as low as 0.7USD/m^3 with the 1.7 million m^3/year size MED with 8 effects based on waste heat recovery from pot gas, while the corresponding number for the same size MED combined with the power plant is approximately 1.1 USD/m^3 which matches the typical production cost reported in the ME region.

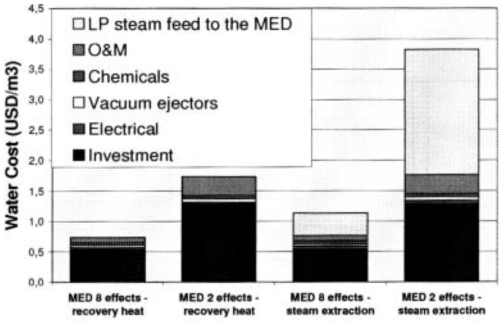

Figure 10 – Specific water production cost for MED

The specific production cost of water from the MED increases for smaller plants since the indirect costs (engineering, etc.) are not proportionally reduced with size, as can be seen in Figures 10 (2 effects compared to the 8 effects). Still, even if no other external users can be relied upon to consume water from the larger size plant with 8 effects, the relatively low investment cost for the smaller plant might still justify the benefits of a secure and dedicated water supply for the aluminium plant.

In the case no desalination plant is installed, the procured cost of water from external suppliers might be significantly higher than the MED production cost of 1.1 USD/m^3 depending on availability and distance from the existing water grid (between 2 to 3USD/m^3).

Energy recovery solutions can improve the CO_2 footprint, and the European CO_2 tax that will be enforced from 2013 includes significant benefits for industries that utilize thermal waste heat. The tax calculation is at the present time highly uncertain, and also depends on the local regulations, and is therefore not included in the present calculations of water cost. It is clear however, that significant CO_2 cuts is possible associated with the use of the heat normally wasted from the pot gas.

Conclusion

Reductions of energy, CO_2 footprint and of water consumption are three major environmental goals for aluminium smelters, especially in areas where water is in scarce supply. This paper has explored the possibility of valorizing heat extracted from pot gases to produce fresh water.

Both the heat exchanger and desalination systems are now mature technologies. The main technical challenge lies in the interface between these two systems, which must take into account the daily and yearly fluctuations in available heat. Preliminary engineering studies have confirmed solutions available for its management.

These studies also suggest that the resulting water cost for the smelter could be equal to or better than potential alternatives while delivering significant benefits in terms of environmental footprint. This evaluation, which implies that the HEX installation is self-justified and that the available heat is therefore free, will depend on local economical conditions.

In these conditions, Alstom and Rio Tinto Alcan believe the integrated production of fresh water is worth considering for new greenfield – and potentially brownfield – projects.

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