Trans Indian Inst Met (2019) 72(8):2135–2150
https://doi.org/10.1007/s12666-019-01699-9

TECHNICAL PAPER

Sustainable Primary Aluminium Production: Technology Status and Future Opportunities

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Received: 8 February 2019 / Accepted: 25 April 2019 / Published online: 14 May 2019

Abstract Energy and greenhouse gas emission remain the major technological challenges to the aluminium production. Over the last few decades, aluminium industries have been aiming for higher production volumes through capacity creep in the existing smelters with reasonable additional investment. However, a strong focus on specific energy consumption has always been part of technology considerations, and this aspect is even more critical today from the point of view of long-term sustainability. Through research and innovations in design, control and operations of Hall–Héroult cell, modern smelters are achieving a benchmark performance as low as 13 kWh/kg of Al at commercial scale and 12 kWh/kg of Al at pilot scale. There is also significant research effort put on alternate technology platforms like drained cathode cell and inert anode. Although there are many pilot-scale demonstrations, many critical issues like operating cost and stability problems in drained cell and higher specific energy in inert anode need to be addressed for commercial consideration of these technologies. Industry 4.0 platform technologies like internet of things, cloud computing, machine learning and artificial intelligence, etc., are opening up further opportunities for benchmark performance to the modern smelters. Digital twin is such an emerging technology for predictive control and operation and will be a key driver for low-energy cells. Based on a discussion on the status of present technology, this article presents a comprehensive review of the technological progress of aluminium smelting and emerging new technology like Industry 4.0, towards reduction of energy and making aluminium production sustainable.

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Keywords Aluminium smelting · Low-energy cell · Process control · Drained cathode cell · Inert anode · Vertical cell · Industry 4.0 · Digital twin

1 Introduction

The demand of aluminium is continuously increasing due to higher consumption in transportations, electronics, building construction and power. While recycling of aluminium is on the rise, primary production is still the major source of aluminium. Worldwide in 2018, primary production is expected to be 64 million tons as compared to 12 million tons through recycling route. The primary production has sustainable challenge from energy, solid waste and emission (CO_2 and PFCs) target. Compared to countries that use hydel power, countries like India that depend on coal-based generation, also face additional challenge of CO_2 emission from power generation.

For many decades, smelters have focused on developing cell with higher current for larger production volumes, while keeping the specific energy consumption low. However, due to ever-increasing power cost, the reduction in specific energy consumption has become more critical for many operations today. To mention, the cost contribution of electrical power in some countries further has increased by costs for indirect CO_2 emissions, or the limitation on production volume when availability of electric energy is limited by power production or grid capacity. The obvious response to these challenges is to lower the specific energy consumption of the primary production process. Figure 1 shows the energy matrix for an

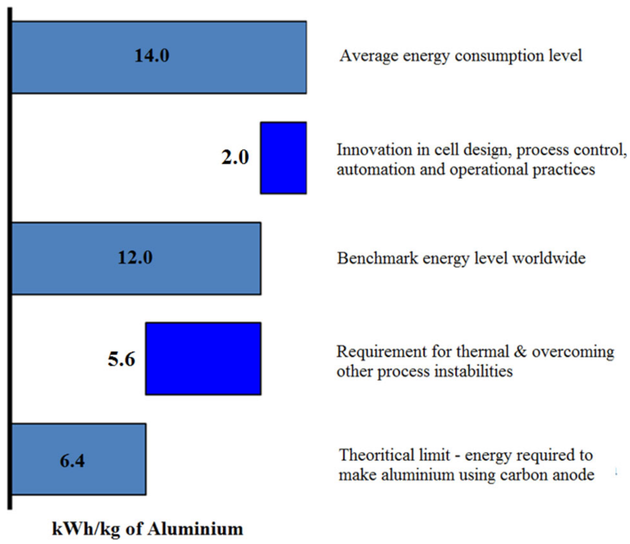


Fig. 1 Energy matrix of an aluminium smelter

aluminium smelter, highlighting the various energy requirement of aluminium smelter.

The theoretical energy requirement to produce aluminium from alumina through electrolytic process using carbon anode is 6.4 kWh/kg of aluminium [1, 2]. For successful electrolysis, cryolite, the only electrolyte, which can dissolve alumina, needs to be maintained in molten state through Joule heating. Hence, the rest of the energy is required to maintain cryolite in molten state and to overcome other process instability.

Over last few years, extensive research is going on to reduce this part of energy. From an average specific energy of 14.0 kWh/kg of Al, aluminium industries are consistently bringing down the energy through incremental design innovations aided by the refined control strategies and operational improvements. Rio Tinto Alcan (RTA), Hydro Aluminium (HAL) and Russian Aluminium (RUSAL) have been actively developing the cell technology, like AP-Xe, HAL4e ultra, RA-550, respectively, which offers benchmark specific energy consumption around 12.0 kWh/kg of aluminium [3–5]. Few Chinese smelters have also reported cell technology running close to this benchmark energy consumption [6, 7]. The cell operation at such low energy will require innovation in design of anode, cathode, cell lining and busbar configuration along with stringent process control to ensure alumina concentration in narrow band. Typically, advanced modelling, field measurements, smart sensors, advanced automations and test pot for trials are the platform for development of such technology. The article will present the current aluminium smelting technology and its improvements over the years through innovation in design, control and operational strategies for achieving the benchmark energy consumption.

In the past, a number of new technologies have also been researched for producing aluminium at lower cost compared to present Hall–Héroult cell, namely drained cathode cell [8–10], inert anode [11–13], vertical electrode cell [14, 15] and carbothermal reduction [16–19], etc. However, none of these technologies has yet become commercially successful. In the recent past, there is renewed interest in both drained cell and inert anode-based technologies [20–22]. A brief review of both these technologies along with some fundamental results will also be presented in later part of this paper.

With significant development in artificial intelligence, machine learning, along with internet of things, cloud computing, big data analytics and simulation technologies, opportunities of leveraging digital technologies in the paradigm of Industry 4.0, is fast emerging to achieve the highest level of operational and performance benchmarks. Digital twin (DT) is one such disruptive digital technology platforms [23], which is a digital replica of a physical system. In the context of smart manufacturing, this article will also discuss DT technology for aluminium production and will show how this can assist aluminium industries in addressing energy and emission challenges.

2 Technology Fundamentals and Present Status

Primary aluminium metal is industrially produced through an electrolytic process also known as Hall–Héroult process. The amperage of an electrolytic smelter ranges from 60 kA to 600 kA depending upon the cell technology. The cells or pots are connected in series in a smelter by aluminium busbars, and DC current flows from one cell to another through these busbars. Within a cell, the current flows downwards through the carbon anodes, the molten electrolyte (cryolite), the molten metal (aluminium) and then to the carbon cathode blocks as shown in Fig. 2. The steel collector bars embedded in the cathode blocks take the current out from the cathodes to the external busbars, which leads to the next cell [24]. The cell lining holds the molten electrolyte, in which the raw material alumina (Al_2O_3) is fed to form the product molten aluminium.

The electrolyte, also known as 'bath', is primarily made up of cryolite (Na_3AlF_6) with some additive such as aluminium fluoride (AlF_3), calcium fluoride (CaF_2) and magnesium fluoride (MgF_2). These additives lower the liquidus temperature to make the cell operation feasible at the temperature close to 920–970 °C [25]. Smelting is a continuous process, with alumina being fed from the top of cell at frequent intervals and dissolved in the molten bath. As the electrolytic reaction proceeds, aluminium, which is slightly denser than the electrolyte, continuously deposits on the top of cathode, i.e. the pool of molten aluminium,

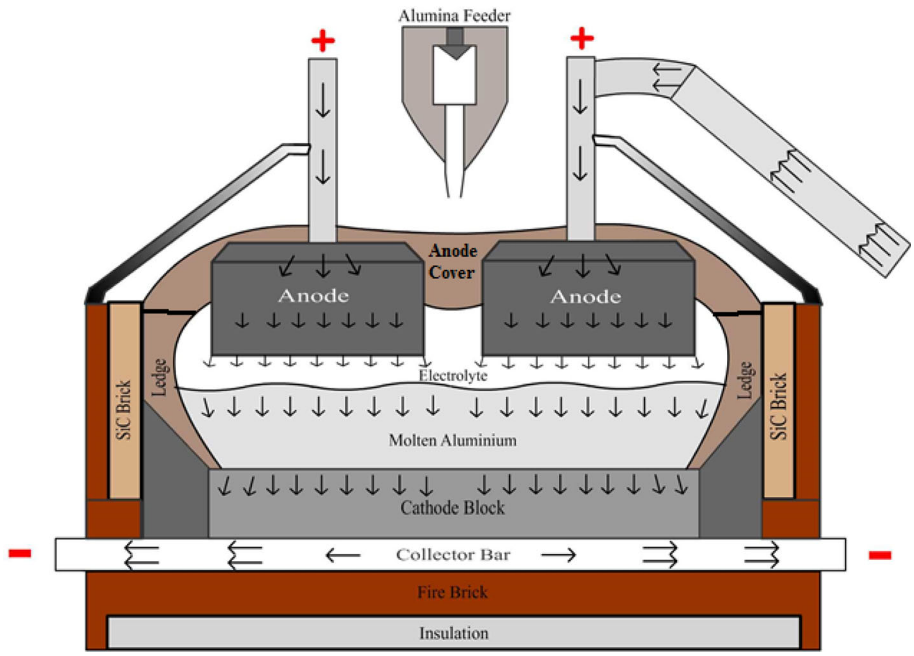


Fig. 2 Cross-sectional view of a typical aluminium smelter

whereas oxygen reacts with the carbon based anodes to form gaseous carbon oxides, which is released as CO_2 gas. During the process, anodes are continuously consumed and replaced at regular interval. The overall reaction for this process is endothermic and represented by Eq. (1) [25].

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \quad (1)$$

The passage of high current (I) through current-carrying components of the cell with total electrical resistance (R) will incur generation of Joule heat inside the cell according to Joule's law (I^2R). The maximum heat generation takes place in the electrolyte region, since it has the highest electrical resistivity compared to any other current-carrying components, which keeps the electrolyte in molten state. At this temperature, the molten electrolyte can corrode or damage the exposed cell lining materials. In order to protect the side lining from the corrosive action of electrolyte, thermal balance of cell is designed in such a way that a frozen layer of the electrolyte, known as ledge (as shown in Fig. 2), is always present during the course of cell operation [24]. Ledge profile and thickness are dependent on the cell design, lining material, line amperage and other process parameters such as anode-to-cathode distance (ACD). Nearly vertical ledge profile with no extension under the shadow of anode helps in attaining good performance and high process efficiency [24].

Strong magnetic fields are generated in and around the pot due to the flow of high electric current through the external busbars and pot components [26, 27]. Combination of the electric current and the magnetic field gives volumetric electromagnetic force, known as Lorentz force. This force is responsible for the movement of metal and bath as well as for the deformation of the metal–bath interface [28]. Magnetohydrodynamics (MHD) is the science that studies the effect of electromagnetic forces on fluid flow, and it plays a key role in deciding cell stability and energy consumption [29–31]. Since bath has the highest electrical resistivity, to keep the energy consumption low, the ACD needs to be as thin as possible subject to satisfying the heat balance requirement and maintaining the MHD stability of metal-electrolyte interface.

Table 1 shows the typical distribution of voltage drop across various components of an aluminium smelter. The split up of reaction voltage has been reported earlier by Haupin [1].

The reaction voltage, i.e. the voltage required to make aluminium, mostly remains same, unless there is scarcity of alumina in the bath, which leads to rise in anodic concentration over potential. The decrease in alumina concentration also enhances the surface tension of the bath thus producing larger gas bubbles underneath anode [32]. Hence, the current density on the active parts of the anode increases, causing a further increase in the over potential to the point where fluoride ions, the next most easily oxidized ions, start to discharge. This forms CF_4 and C_2F_4 surface compounds that have very low surface energy and cause complete non-wetting of the anode [32]. This results in a continuous gas film between the anode and the bath leading to current flow by sparking or arcing across this film. Since the cells operate at constant current, this produces a large increase in voltage, termed as anode effect (AE) [32]. To avoid the AE, alumina concentration of the cell needs to be controlled effectively through a tight process control. The

Table 1 Typical voltage breakup of an electrolytic cell

Cell Component	Voltage (V)
Anode voltage drop (AVD)	**0.350**
Cathode voltage drop (CVD)	**0.300**
External busbar	**0.150**
Gas bubble layer	**0.250**
Electrolytic bath (in ACD)	**1.540**
Reaction voltage	**1.756**
Decomposition potential	1.222
Anodic surface over potential	0.466
Anodic concentration over potential	0.036
Cathodic concentration over potential	0.032
Total cell voltage	**4.346**

The summation of bold values gives total cell voltage

desired alumina concentration in bath is usually 2–3% for good cell control and operation to attain higher energy efficiency [33]. With increasing cell sizes and current intensity, alumina dissolution and its distribution becomes critical, which requires systematic analysis to decide on number of feeders, feed size and location of feeder for efficient cell operation [34]. With the advent of point feeding technology and advances with computer-enabled operation, periodic AE has almost seized to exist [33].

Since maximum voltage drop takes place in ACD, major effort has been reported to lower this by improving the stability of the metal–bath interface through optimization of busbars configuration [27–29, 35, 36]. Beside optimizing the magnetic field, reduction in the horizontal current is another way to improve the stability of cells and thus reduce ACD. In the slotted anode design [37, 38], longitudinal or transverse slots are incorporated in the anode bottom which helps in escaping of the gas bubbles and thus reduces the voltage drop from gas bubble layer underneath the anode. Likewise, anode and cathode have also been focused for lowering the voltage drop by improving the contacts/joints between dissimilar materials as well as incorporating the new materials with low electrical resistivity.

3 Low-Energy Hall–Héroult Cell Technology

The energy reduction solutions for the existing smelting technology require innovation in cell design, materials and control strategies along with operational excellence. Reduction in ACD through improvement in MHD stability is associated with other challenges such as the thermal imbalance, alumina feed control due to reduced bath volume and the pot life. Typically, the low-amperage cell (< 100 kA) works on heat conservation mode due to high ratio of 'surface area for heat loss' to 'internal heat generation' and thus requires a minimum ACD of about 45–50 mm to ensure the thermal balance and avoid associated problems. On the contrary, for the high-amperage cell, this ratio is comparatively low; hence, it works on heat dissipation mode and has more potential to squeeze the ACD up to 30 mm, provided the cell remains MHD stable.

3.1 Cell Design: Modelling and Measurements

The MHD stability of a cell typically refers to the stability of interface between the molten electrolyte and molten aluminium. The interface stability has strong reliance on the electromagnetic forces originated form the interaction of the horizontal current and the vertical magnetic field [29]. Hence, to enhance MHD stability, the magnetic fields should be compensated to have low and balanced values of the vertical magnetic field (B_z) [29, 35, 36, 39, 40]. Figure 3 shows that there are two types of magnetic compensation; (b, c) external current compensation where the current used for compensation is independent of the line current and (d) internal current compensation where the line current itself is used for compensation [28].

Figure 4 shows the results from an electromagnetic model highlighting the impact of these compensation designs on vertical magnetic field [28]. Here, the internal current compensation offers good result as it provides the desired symmetrical opposite values by balancing off the effect arising from neighbouring line.

Improved magnetic field distribution by means of compensation alters the electromagnetic forces, which are responsible for MHD performance of the cell. Table 2 shows the comparison of MHD model results for an existing busbar design with an internal current compensation design as shown in Fig. 3a, d [28]. It can be seen that the metal velocity becomes uniform and lower in magnitude with the magnetic compensation. Lower metal velocity and lower deformation of metal–bath interface reduce the back reaction and help in improving the current efficiency.

The latest technologies such as AP-Xe, HAL4e-ultra reportedly have busbar compensation which have risers, only entering from one side (upstream), whereas RA-550 has risers entering from both sides (upstream and downstream) of the pot [3–5]. Riser entry from both the sides manages to lower B_z significantly with a possibility of future scale-up with lesser modification [4]. These technologies offer excellent MHD performance with respect to flow profile and stable metal–bath interface. These improvements in MHD stability may offer an ACD close to 30–35 mm and help in achieving the benchmark energy consumption of about 12.0 kWh/kg of Al.

Alternatively, the Cu-inserted collector bar (CuCB) also improves the MHD stability by reducing the horizontal

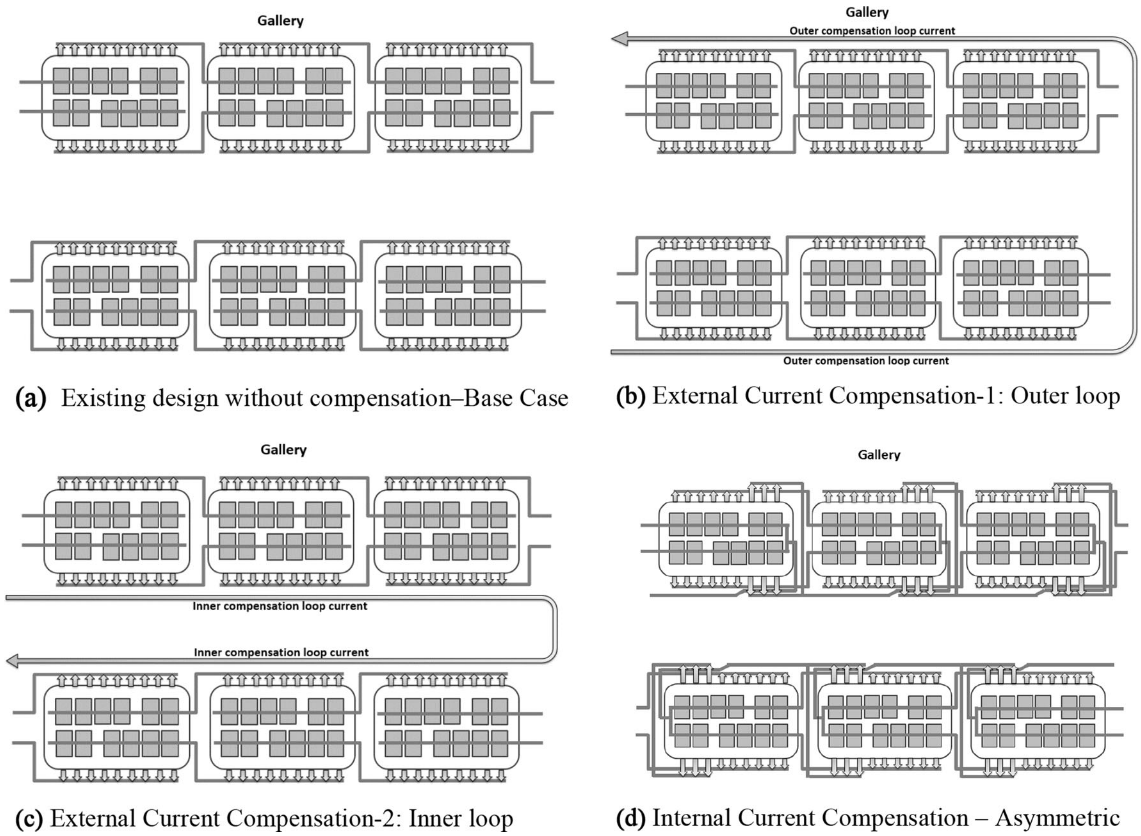


Fig. 3 Typical designs of magnetic busbar compensation [28]

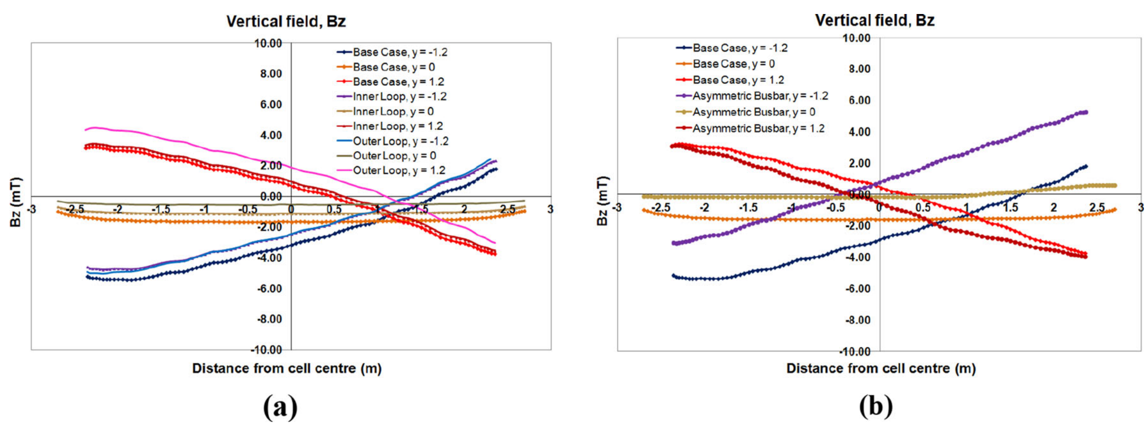


Fig. 4 Comparison of B_z for the existing design with **a** external current compensation and **b** internal current compensation [28]

current component [41, 42]. Figure 5 shows that the presence of copper in the collector bar lowers the resistance R_2 significantly, thus allowing the almost similar resistance path throughout the cathode assembly. The new resistance distribution of cathode assembly helps in obtaining nearly vertical current distribution, thereby reduction in generation of horizontal current in molten aluminium.

Recent development on CuCB has been widely adopted by smelters worldwide to enhance the MHD stability through reduction in horizontal current [41–43]. Apart from improvement in MHD stability, CuCB also reduces the cathode voltage drop (CVD), attributed to uniform current distribution in the cathode and lower electrical resistivity of copper. The utilization of CuCB has demonstrated energy saving of about 0.3–1.0 kWh/kg of aluminium, depending on cell technology [41, 42].

Additionally, the cathode material with higher graphitization also reduces the CVD due to low electrical resistivity; however, it enhances the generation of horizontal currents. Increased height-to-width ratio of collector bar

Table 2 Comparison of MHD parameters in an 85-kA end-to-end pot

Parameters	Existing busbar design without compensation	Internal current compensation—asymmetric
Average velocity	5.9 cm/s	5.0 cm/s
Maximum velocity	21.9 cm/s	12.8 cm/s
Percentage above 10 cm/s	27.0%	9.6%
Percentage below 5 cm/s	37.9%	43.7%
Metal–bath interface deformation (max–min)	5.5 cm	3.5 cm
Location of interface maxima	Near downstream end of pot	Near centre of the pot

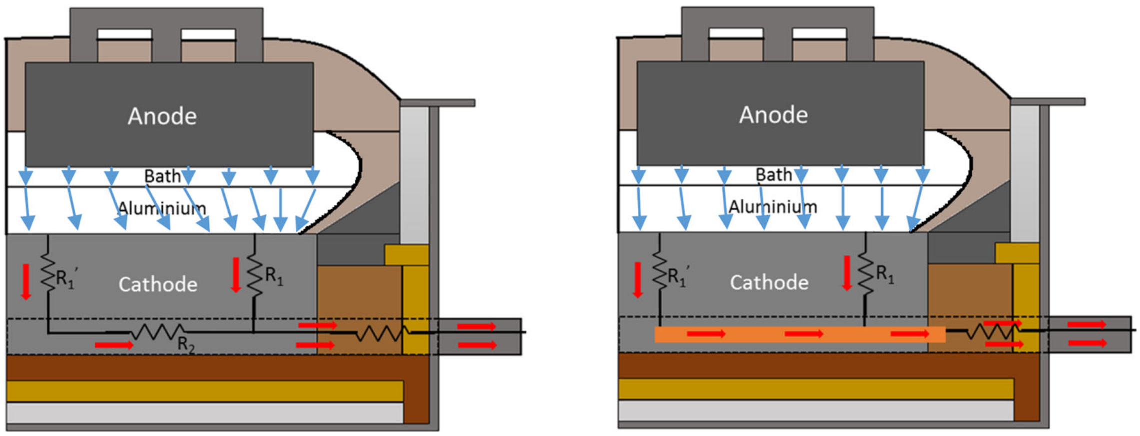


Fig. 5 CuCB impact on cathode assembly resistance and current distribution

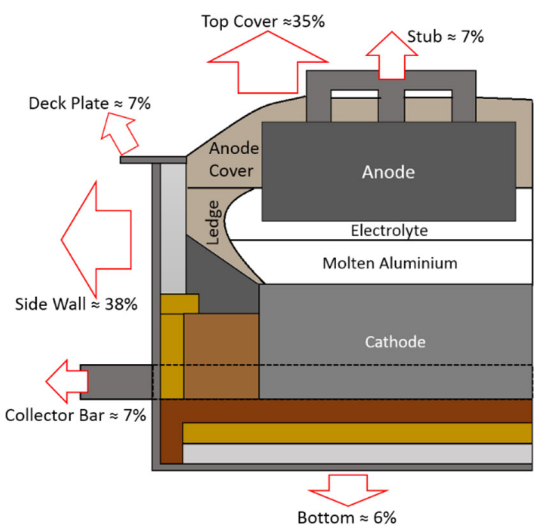


Fig. 6 Typical heat loss distribution from an aluminium reduction cell

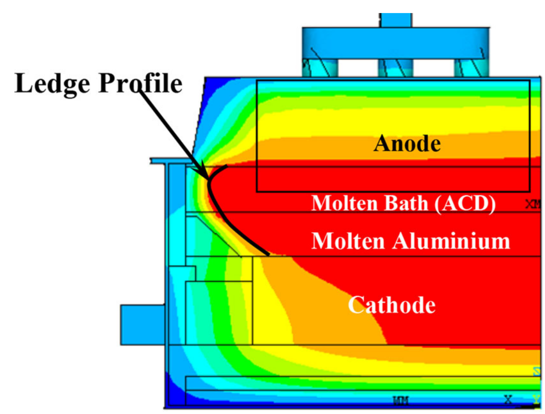


Fig. 7 Typical thermal and ledge profile obtained from thermo-electric model

also reduces CVD, but enhances the generation of horizontal currents [44]. Hence, cathode and collector bar assembly needs a holistic analysis for improvement in the current distribution for enhancing the MHD stability along with lower CVD. To maximize the benefits of energy reduction approaches, the thermal balance of cell also needs to be carefully analysed and re-establish for modified conditions by optimizing cell lining design and process parameters. Typical heat loss distribution from a Hall–Héroult cell is shown in Fig. 6.

The computational models play a crucial role in analysing any design modification and its impact on heat loss distribution, thereby ensuring an improved thermal balance and ledge profile for greater energy efficiency of the cell [24, 44–46]. Figure 7 shows the model predicted

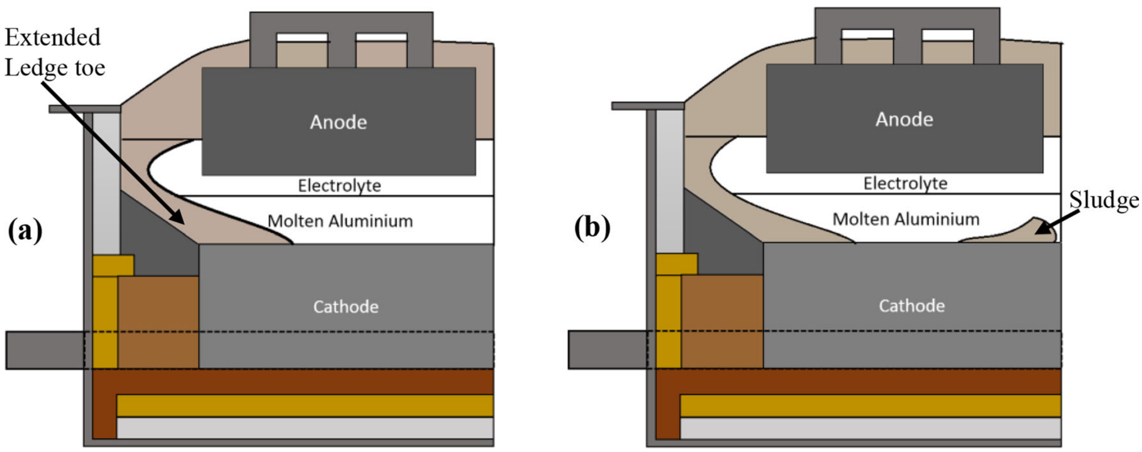


Fig. 8 Impact of thermal imbalance: **a** ledge extended under the shadow of anode and **b** sludge formation over the cathode surface

temperature isotherms in a pot, wherein tracking of the liquidus isotherm in molten electrolyte and molten metal region gives the freeze/ledge profile.

The dynamics of ledge profile and response characteristics on the long sides, short ends and in the cell corners becomes very critical for low ACD operation. An improper thermal balance may lead to freezing of the electrolyte on the cathode carbon surface with ledge toe extension under the shadow of anode. Additionally, it may enhance the occurrence of sludge/muck formation as shown in Fig. 8.

The presence of extensive ledge and sludge can lead to uneven current distribution in the cell and adversely affect the MHD stability of a cell. Hence, for low ACD operation and good performance of cell, less cathode temperature gradient and nearly vertical ledge profile should be ensured, while designing the cell refractory lining.

3.1.1 Measurements

Computational models that predicts thermal, electric, magnetic and MHD aspects of an aluminium reduction cell, are heavily used by the industries for optimization of the existing cell as well as development of new cells for superior economic and environmental performance [4]. A protocol of rigorous validation and calibration with detailed pot measurement has been adopted by industries before using the models for evaluation and optimization of pot designs. Special measurements like temperature, heat fluxes, ledge profile, magnetic field and molten metal velocities are carried out in the field. A discussion on model validation with measurement data from a representative live pot is presented in the section below.

Ledge profile of a cell is a direct indicator of pot thermal balance. Figure 9 shows measured ledge profile compared with ledge profile predicted by the thermo-electric model

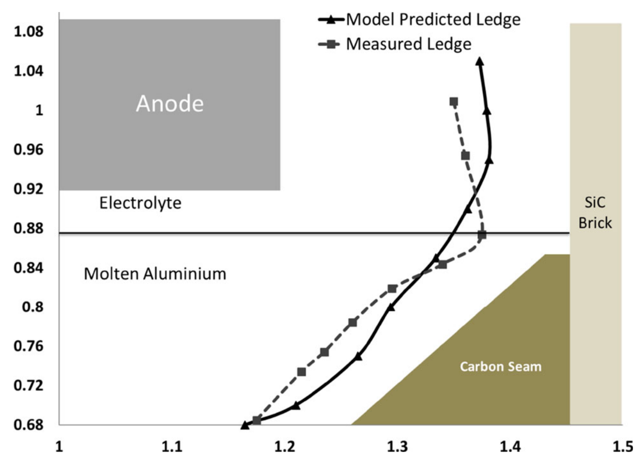


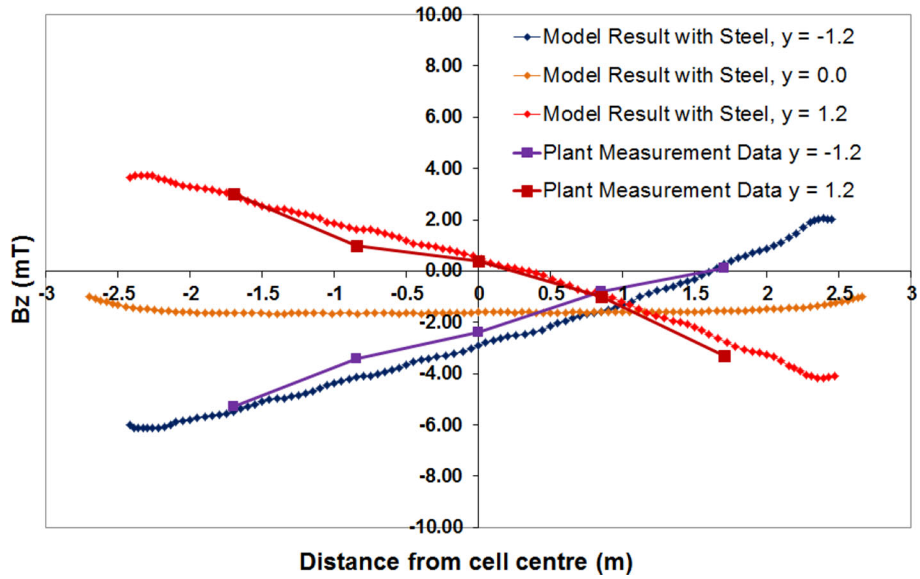
Fig. 9 Ledge profile comparison for model prediction vs measurement

of representative pot. Model prediction seems to be in congruence with measurement data [24].

Similarly, measured vertical magnetic field, i.e. B_z values inside the pot of an 85 kA smelter, is compared with electromagnetic model prediction in Fig. 10 that shows close conformance. These measurements have been taken from both the side channels of a pot and near the anode edge at mid-height of the metal pad [28].

Molten metal velocities, predicted by MHD model, have been compared with the measured velocities in the running pot. To measure the velocity, iron rod dissolution method has been used where high purity (99.5%) iron rods is inserted into the molten metal for a specified duration [8]; rate of dissolution is calibrated with the local velocity. The moving molten aluminium dissolves the iron rods in such a way that a careful examination of the erosion pattern on rod surface provides the velocity direction. Figure 11 shows the model predicted velocities as compared with measured velocities in the molten aluminium [47].

Fig. 10 Comparison of model predicted vs measured vertical magnetic field Bz (mT) [28]



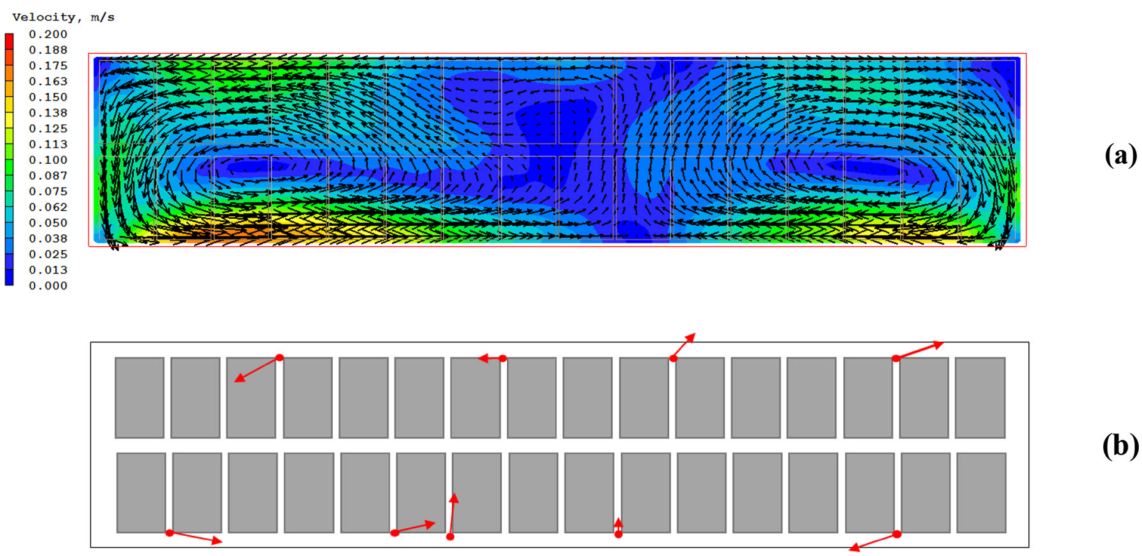


Fig. 11 Metal flow profile at mid-height of metal: **a** simulated vs **b** measured

The size of the arrow indicates the magnitude of measured metal velocity at that location and the overall velocity was found in the range of 0.03–0.18 m/s. The measured flow pattern and velocities are reported to be in close conformance with the predicted flow profile by the MHD model [47].

3.2 Process Control, Automation and Heat Recovery

The process control of an aluminium smelter has evolved over the years, through development in hardware and software. Nowadays process control is not only used for cell control but also for the technical management of modern smelter. The improvement in energy efficiency of a smelter requires an automatic cell control system, which manages the alumina feeding, cell resistance regulation (i.e. ACD control), bath chemistry, cell heat balance as well as some routine operations [48]. The energy reduction initiative, which focuses primarily on lowering the ACD, reduces the bath volume thus making it challenging to control the alumina concentration in the pot. Hence, to ensure a good cell control, research focus has been on lowering the feed size, determining the new decision criteria for detecting the AE and killing it fast, while running the cell in that narrow band of 2–3% of alumina concentration [33].

Alumina feeding strategy plays a crucial role in smooth functioning of process and ensuring minimum anode effect.

Based on the real-time voltage measurement, alumina feeding in each pot is activated by modern PLC-based control system. The logic of the control system is based on the target alumina concentration along with design and operational experience of each smelting plants [49]. Close monitoring of voltage and alumina feeding is critical to operate the pots with minimum AE and highest current efficiency [32]. The accurate feeding of alumina into the electrolyte/bath depends on feeder hole opening, which relies on crust breaker efficiency. Pneumatic crust breaker operation is often a compromise between long crust breaking time for better opening of blocked holes and short residence time in the bath. New technology such as chisel bath contact ensures that crust breaker makes a contact with the bath for accurate alumina feeding. This technology is very much essential for energy reduction solutions as low ACD reduces the electrolyte volume and requires inevitability of alumina [50, 51].

The variability in the process parameter plays a crucial role in defining energy efficiency of the process. Worldwide researchers have been working on to reduce variability by increased accuracy, repeatability and avoidance of human factors. The advancement in pot tending machines (PTM) [52] has automated most of manual intensive activities such as top crust breaking, anode change resulting in smooth performance, while promoting a safe working atmosphere [53, 54]. With the advent of online in situ gas analysers, the real-time information on emissions such as HF, SOx and CO_2 can also be obtained, which will be helpful in maintaining the process in the desired operating range [55, 56].

Another important aspect of energy reduction is the heat recovery and utilization. In principle, three major heat sources can be identified in a modern cell: (a) heat losses from the steel shell wall, (b) heat energy in the exhaust gas stream and (c) heat losses from the stubs/yokes or top anode surface. HAL utilizes a distributed suction system, which allows combining the benefits of a higher CO_2 gas concentration in the exhaust gas for further processing in a carbon capture and storage solution with the increased efficiency of heat usage [57]. The heat loss from steel shell sidewall plays an important role in thermal balance and defining the shape and size of ledge. Precise control and regulation of sidewall heat recovery can further improve the cell performance and energy consumption, which opens up an opportunity to regulate the cell amperage by about $\pm$ 20% [58, 59].

The development of low-energy aluminium smelting technology has not only helped in addressing the cost pressure due to ever-increasing electricity prices, but also reduces the environmental impact. Energy being the key driver of aluminium production, alternative processes/methods/technologies have also been investigated by researchers to reduce the energy requirement and environmental footprint of the present aluminium industry and these are discussed in the next section.

4 Alternate Technologies for Primary Aluminium Production

The cost and economic challenges associated with the present Hall–Héroult process have led the intensive research to find alternate routes for aluminium production. One such process is the direct carbothermal reduction of alumina to aluminium using carbon and heat, which has potential for larger productivity, lower investment, less electric power consumption and lower overall greenhouse gas emission, compared to the existing Hall–Héroult process [16–19]. However, this process is yet to reach the commercialization due to the problems associated with extreme operating conditions and low aluminium yield [60].

Other technologies such as drained cathode cell (DCC) and inert anode still utilize the electrolytic route for aluminium production and have been researched deeply. Both of these technologies show promising potential for retrofit in the existing infrastructure to lower the capital requirement. A brief review of these two technologies is presented subsequently.

4.1 Drained Cathode Cell

The DCC shown in Fig. 12 allows the produced molten aluminium to be drained from the cathode to a separate collection sites. By eliminating the metal pad, magnetically induced instability can be avoided and ACD could be reduced to about 20 mm, enabling substantial voltage lowering [8]. Since 1970s, more attention has been drawn to this concept, and many designs have been filed for patents [10, 61–64]. During 1990s, COMALCO, which is now owned by RTA, had tested concept of DCC in few trial cells [65]. Few Chinese smelters have also reported small-scale trials at lower amperages; however, commercial implementation in full line is still awaited.

While this technology has an immense opportunity, there is not yet full-scale demonstration of this technology reported in the literature. There are design challenges and critical areas that need to be addressed for techno-commercial feasibility of a DCC. For instance, the fundamental understanding of two-phase gas–liquid hydrodynamics is required to operate at such a low ACD. This should be the basis of anode design parameters like optimum electrode inclination. It would also require an in-depth analysis of thermal balance to develop pot operational strategies (like anode change, metal tapping, etc.) in commercial scale.

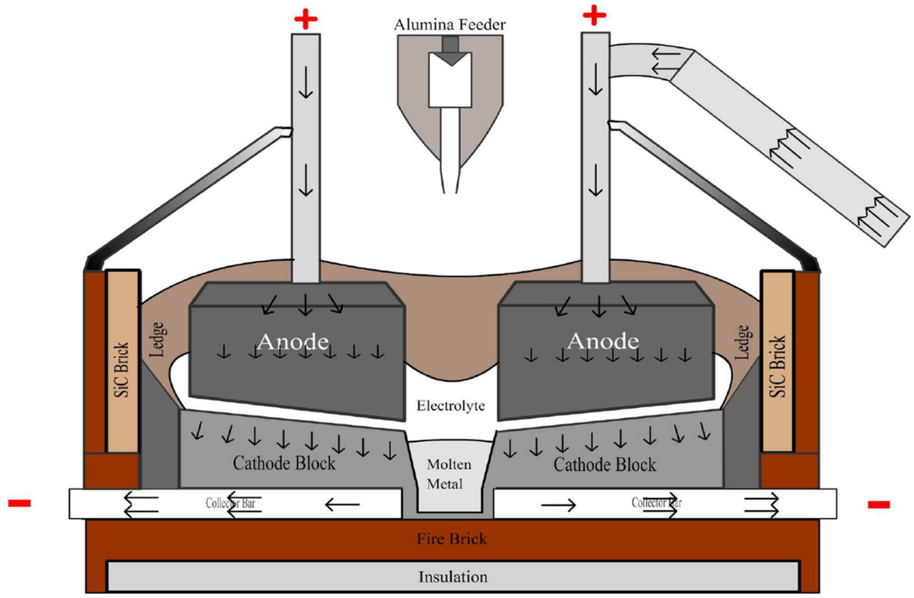


Fig. 12 Schematic of a drained cathode cell

The alumina feeding needs to ensure fast dissolution and distribution in the reduced electrolyte volume, as non-availability of alumina under a single anode would trigger the anode effect. Even then, if anode effect occurs, a mechanism needs to be developed to extinguish it.

Since the molten metal has poor wettability with the present carbon cathode, metal may not cover the full cathode surface and may lead to form some patches where electrolyte can be exposed to the cathode. Therefore, cathode needs to be protected from the corrosive behaviour of the electrolyte. Inert TiB_2-based cathode has been evaluated as wettable cathode for these cells [65]. However, the longevity of coated cathode to make the technology commercially feasible remains a challenge and is an active area of research [66–68].

In view of these challenges, applied as well as fundamental researches have been carried out to address some of these challenges such as thermal balance of DCC, gas bubble and liquid hydrodynamics inside the DCC, to make a step closer towards the commercial success [69–73]. Based on the physical model experiments carried out, the flow characteristics due to gas bubble in DCC are summarized in Fig. 13. These experiments have been performed at gas flow rate equivalent to 8 kA/m^2 and 0.02 m of anode-to-cathode gap for different anode inclinations $1° < \theta < 5.5°$ [71].

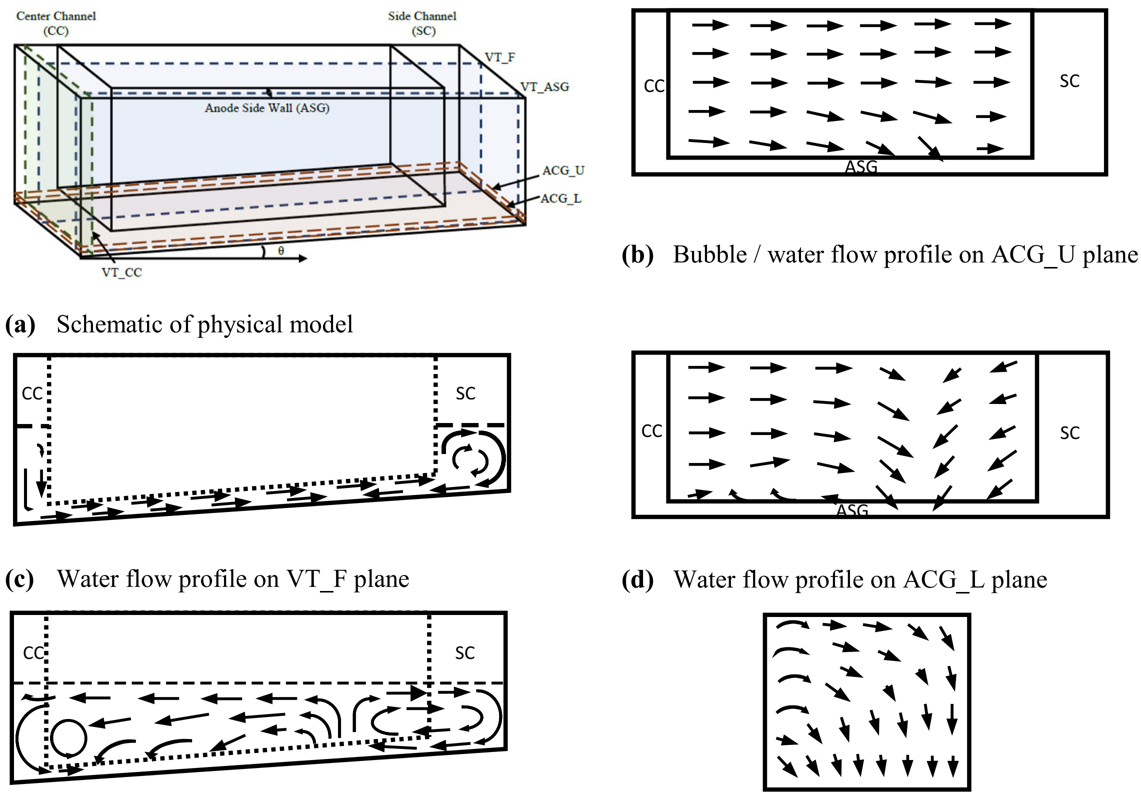
The bubble size distribution and in turn the flow characteristics are seen to change significantly until an anode inclinations of $\theta = 3.5°$. With an increase in θ, the bubbles move faster due to the greater buoyancy force. This reduces the coalescence probability and hence reduces coalescence rate, resulting in reduced number of larger bubbles. In addition, it is noted that the flow pattern in ACD is recirculatory and hence can have significant impact on the alumina dissolutions [71].

This study reveals that the hydrodynamics of gas bubble, liquid flow and alumina dissolutions in a DCC could be controlled through anode and cell design and high-energy efficiency can be achieved. However, due to continuous liquid movement close to the cathode wall, the electrode surface will become non-uniform with time, which will adversely affect the longevity of consistent energy efficient performance of a DCC [71]. The ongoing development in process control systems including software, hardware and sensors will eventually support process control to enhance the operational efficiency of DCC. Drained cathode cell may offer better performance, when coupled with inert anode technology.

4.2 Inert Anode and Vertical Electrode Cell

Inert anodes can significantly improve the aluminium production process by eliminating the need for regular replacement of the carbon anodes. Inert anodes are chemically non-reactive and are not consumed by the electrolysis reaction and thus could ideally have the same lifetime as the smelting cell. Compared to conventional Hall–Héroult smelting with carbon anodes, inert anodes can have the following benefits [74]:

- Reducing cost of production and replacement of the consumable carbon anode. Capital costs for inert anodes could be 10–30% lower than that for conventional one.
- Inert anodes produce oxygen, thus eliminating greenhouse gases produced by electrolysis with carbon anodes (CO_2, CO and PFCs).



(a) Schematic of physical model

(b) Bubble / water flow profile on ACG_U plane

(c) Water flow profile on VT_F plane

(d) Water flow profile on ACG_L plane

(e) Water flow profile on VT_ASG plane

(f) Water flow profile on VT_CC plane as seen from right side

Fig. 13 Schematic representation of overall flow profile in the physical model

- Improving occupational health by eliminating the regular replacement of carbon anodes in the smelting cells and also improving plant-operating efficiency by eliminating anode effects.

For commercial readiness of inert anode technology, the material, design, energy and process control requirement need to be addressed. The following section presents the review of inert anode technology addressing these requirements.

4.2.1 Materials and Design

A major barrier to designing inert anodes is finding cost-efficient anode materials that does not corrode significantly in the reaction solvent. In case the inert anode corrodes, the compound/elements will go into the electrolyte and will potentially affect the purity of aluminium produced. Hence, the longevity of anode is crucial for producing high purity of metal during cell life [75]. Materials that have been considered for development of inert anode include ceramics, metals and cermet, a mix of these two. Table 3 presents the comparison of these three materials with their pros and cons [12, 20, 76].

Out of three, the metal-based inert anode seems to more promising. However, two important points must be addressed while designing this inert anode: (a) oxygen gas that is evolved at the anodic surface has to be removed quickly as soon as it is evolved to reduce the corrosion rate of the inert anode and (b) anodic geometry should be designed such that anodic current density is lower to have higher anode life [76].

4.2.2 Energy Balance

The decomposition voltage for inert anode will be about 2.2 V, as compared to carbon anode, which offers about 1.2 volts. Although the anode polarization is slightly lower in the case of inert anodes, the theoretical energy requirement to make the aluminium will be close to 9.2 kWh/kg as compared to 6.4 kWh/kg of Al for conventional process [77]. To compensate this extra energy requirement, reduction in voltage of electrode assembly, joints/contacts and ACD are typically opted. Inert anode retrofitted in the existing cell may require almost similar ACD limited by thermal balance and MHD stability requirements of cell. Since regular access of the cells to change the anodes is not

Table 3 Materials for inert anode: pros and cons

	Ceramics	Metals	Cermet
Composition	Oxides of Ni, Sn, Fe and Cu; individual or combination	Ni, Fe, Cu and Ag in pure or alloy form	A mix of ceramic and metals
Advantages	Good chemical stability	Easy to manufacture, non-brittle, high electrical conductivity, Electrical connection	Good chemical stability, good electrical conductivity and toughness
Challenges	Very low electrical conductivity, high solubility in electrolyte, contamination of aluminium metal, poor thermal shock resistance and operational hurdles	Unstable in the presence of oxygen at high temperatures, require a thin self-repairing oxide layer with low solubility in the molten electrolyte	Contamination of aluminium metal, electrical connection, sustaining material properties during operational life

necessary, the cells can be sealed more effectively to improve the thermal balance and save energy to some extent. However, it may not be economical replacing carbon anode with inert anode in the existing cell footprint, only from the energy point of view. The inert anode technology may offer some benefits with drained cell due to reduced operation ACD of about 20 mm; nevertheless, the substantial benefits may arise from vertical electrode cell configuration. A vertical cell consists of inert anodes and wettable cathode, and the ACD can be further squeezed below to a level of 10–15 mm, and since many electrodes are possible to be stacked in parallel as depicted in Fig. 14, the heat generation per unit volume would be higher compared to conventional cell or DCC retrofitted with inert anode.

The vertical cell will certainly offer much better energy balance, provided the cell refractory lining material and design issues are adequately addressed. In addition, these cells will require a new cell control system and logic to ensure the availability of alumina near electrodes.

4.2.3 Process Control

For cell operation with inert anode, near saturation concentration of alumina in the electrolyte is recommended to keep the solubility of anode's oxide component (or anode protective film) at acceptably low level [75]. There will be serious problem if alumina concentration is inadequately controlled as undersaturation will cause anode to react and oversaturation will lead to sludge formation. Maintaining near saturation concentration will require new procedure, sensors and control devices [77]. In vertical cell configuration, the availability and concentration level of alumina depends on the molten fluid movements and eventually the driving force for fluid flow.

Research on inert anode for electrolytic production of aluminium has spanned many years. Regardless of the quality of work by engineers and scientists worldwide, most of these efforts have resulted in technical dead ends

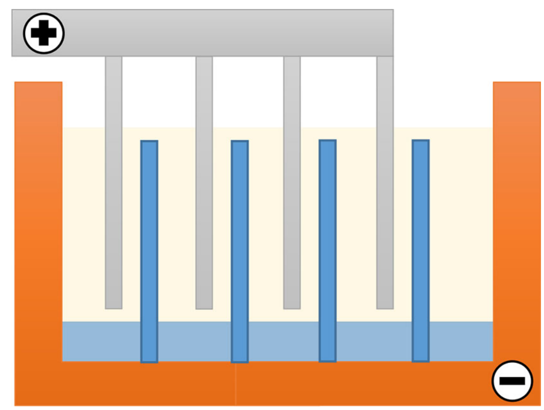


Fig. 14 Schematic of vertical cell configuration with inert anodes and wettable cathode

and bench scale successes could not be translated into workable commercial scale-up. In 2018, ALCOA, RTA and Apple jointly announced the ELYSIS technology for aluminium production, which uses inert anode. It has claimed to extend anode life by around 30 times (about 2.5 years) as compared to carbon anode and reduce the operating cost by 15% and increase productivity [21]. The commercialization of this technology is expected in 2024.

The overall economics may favour retrofitting in the existing smelter, potentially due to elimination of carbon plant, whereas manufacturing cost of inert anode needs to be adjusted. Compared to the benchmark Hall–Héroult cell with 12.0 kWh/kg of Al, the inert anode cell consumes 14.9 kWh/kg of Al, and hence, the effective emission of greenhouse gases will probably be more for inert anode cells for coal-based power [77]. The longevity of inert anode, quality of metal produced and the economics of whole process play an important role for commercialization. Considering the commercial and operational challenges for utilizing inert anode, it is beneficial with vertical cell configuration for long-term utilization and this means that the current layout/footprint of aluminium smelter will not likely to be retrofitted or leveraged.

5 Smart Manufacturing and Industry 4.0

Over the decades, the sustainability of aluminium industry is principally ensured by improving the existing process with the aid of computers and automation. Aluminium smelting is a complex process, comprising production areas: power, material handling, carbon, reduction and cast house, operating as separate units, while remaining interdependent (Fig. 15). A combination of batch, semi-batch and continuous processes creates a dynamic environment, where the changes in one part of the process can have a significant effect on others. Problems in one area can even bring the entire operation to a halt, resulting in high costs and materials loss. Electric power represents about 35–45% of the cost of producing aluminium. Energy consumption and raw materials are two of the primary cost drivers in the aluminium industry, and they tend to go upward, especially when a process deviates from its optimum.

Industry 4.0 introduces the concept of 'smart factory' in which computers and automation will come together in an entirely new way, assisted by smart sensors, internet of things, cloud computing, big data, machine learning and artificial intelligence. It can learn and control the process with very little input from human operators [78]. In a digitally enabled smelter, operators are able to deliver more-efficient and precise operations, which can translate into a reduced energy cost, raw material economization as well as a lesser environmental impact.

Digital twin (DT) is a digital replica of the aluminium smelter seamlessly integrated with the plant operation and control system leveraging the Industry 4.0 technology platforms as highlighted above. Based on real-time plant and process data, DT will continuously generate new data and insights into smelter performance forecast potential challenges like deviations and disruptions, advice operational remedies, generate process control actions and allow plant managers and operators to run the smelters efficiently to a benchmark performance. DT technology is in early stage of development, and with maturity of the platform, this will disrupt the manufacturing technology within next one decade.

The digital model of the smelter that runs in real time and forecasts performance is a key element of the DT. These digital models are based on design and operating information of the plant and process using historical and real-time data. Data analytic techniques, including machine learning, are generally used to build data-based models, which can be integrated with first principle-based models to enhance the robustness of these digital models remarkably. On successful incorporation, it will account for any unforeseen process deviations and in turn ensure high degree of reliability of DT. Reduced ordered model (ROM) technology is a fast emerging viable option to incorporate the first principle information in a real-time framework [79] and will be a foundation for successful development of DT of aluminium smelter. This is explained in the overall architecture of aluminium smelter DT presented in Fig. 16. The proposed framework addresses all the key process areas that control the smelter performance and generates decision advice for plants like fast recovery from disturbances, efficient performance and longevity of pot.

As shown in Fig. 16, DT will combine the data from various sensors/observations with the first principle-based model to depict the live pot condition. Use of artificial intelligence (AI) technology will enable creating a self-tuning live model of the smelters. Each pot/cell will be treated as individual asset for optimization of process parameters. This will serve as the foundation for various

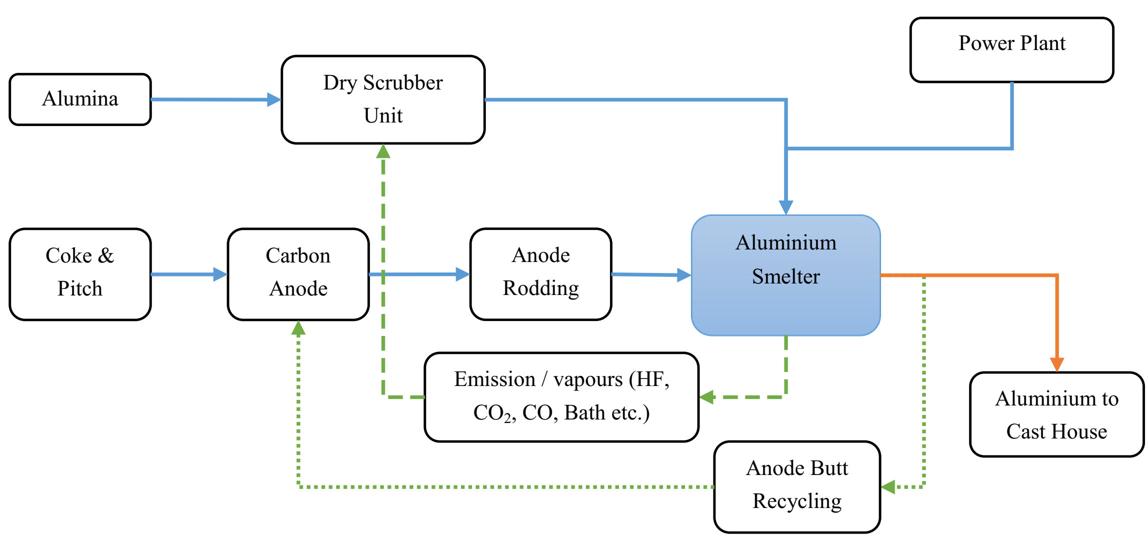


Fig. 15 Overall process flow of an aluminium smelter plant

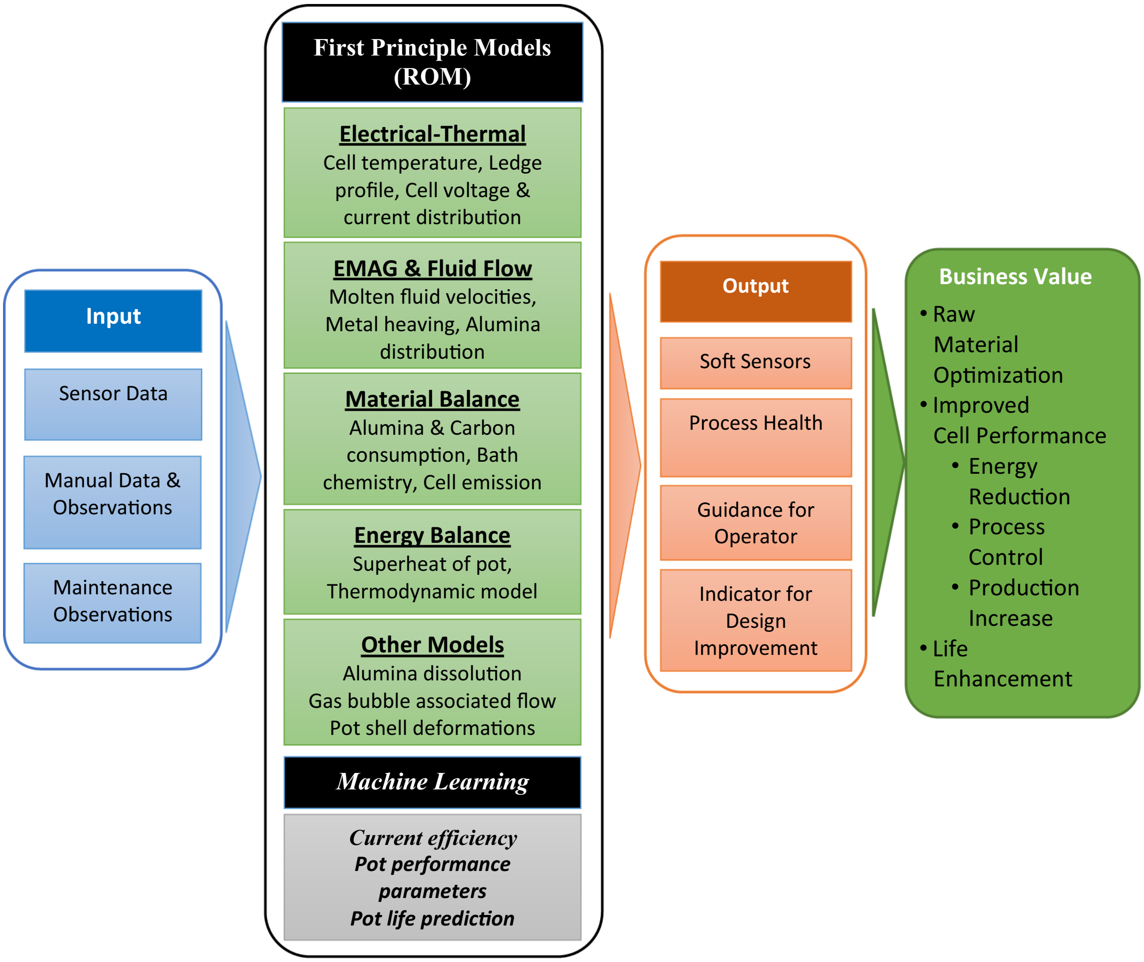


Fig. 16 Typical architecture of digital twin of an aluminium smelter

applications that contribute to the enhancement of the efficiency, productivity and reliability of the smelting process. Consistently monitoring variety of factors and utilizing the solutions of predictive analytics will enhance smelting process efficiency by lowering raw material's consumption, decreasing energy consumption and reducing pot leakages.

DT can provide key intelligence on process variables such as temperature and compositions within the smelting pot, not ordinarily monitored continuously. When compared against the real-time data, it can spot actual or potential abnormalities and failures before they occur and provide real-time feedback to the operator. The insights empower operators to anticipate the health and condition of the pot and result in faster specific interventions, characterized set points for optimum operation and reduced losses from unplanned downtime or even major failures.

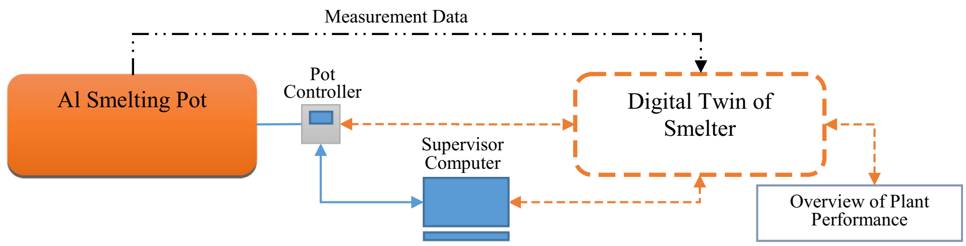
Figure 17 presents how DT will be integrated in the plant automation system and as a part of supervisory control system. While DT will continuously download process control advices to the supervisory computer, a dashboard of plant data vis-à-vis benchmark and potential future process anomalies will enable the operators and managers achieving consistent and benchmark performance. Although each production area needed its own discrete network to isolate it from problems in any other area, overall efficiencies and quality can only be maximized by sharing such information through digitization.

With the development and successful deployment across manufacturing industries, Industry 4.0-based technology solutions will be integral part of modern smelters and adopted by the existing plants in order to achieve sustainability goals and remain competitive.

6 Summary and Conclusion

The present aluminium smelters have been striving hard to bring down the energy consumption, which has helped them to remain competitive. Based on new developments in design modelling, measurement and control strategies, lining, anode and cathode materials and operational

Fig. 17 Digital twin in plant automation architecture



practices, the aluminium smelting plants are continuously improving energy consumption through various incremental innovations.

Through step-change innovations in design, control strategies and operational practices, AP-Xe, HAL4e ultra, RA-550 have reached the benchmark specific energy consumption of about 12.0 kWh/kg of aluminium, at pilot scale. These cells operate at significantly low ACD of about 30 mm, which has been only possible through advanced modelling, field measurements, smart sensors and advanced automation. With the new developments in low-energy cell technology, the integration of heat utilization technology with efficient heat recovery system provides a great potential for further reduction in energy consumption.

DCC and inert anode are two disruptive innovations that have been researched for a long time by academia and industries with a potential to retrofit in the Hall–Héroult cell. While there are pilot-scale demonstrations for both these technologies, full-scale commercial plant is yet to be established, largely due to higher operating cost and problems. For example, the longevity of electrode profile during operation, cathode materials, process control is still a challenge for DCC. Inert anode in vertical cell configuration has potential to reduce the operating cost by about 15% with increased productivity. However, inert anode technology retrofitted in the existing smelter, which utilizes coal-based power, may not be favourable to reduce the carbon footprint due to higher energy requirement for cell operation.

With fast pace development in Industry 4.0 technology platforms (like internet of things, cloud technology, machine learning, artificial intelligence, etc.), digital twin will be a new disruptive technology intervention in aluminium smelting that will enable industries to achieve the highest level of operational and performance benchmark in energy and emissions.

Acknowledgements The authors would like to thank their colleagues in HINDALCO and Aditya Birla Science & Technology Company Pvt Ltd. (ABSTCPL) for their contributions over decade-long research programs on sustainable aluminium production. Authors also thankfully acknowledge the collaboration with Prof Rajiv Shekhar, Indian Institute of Technology, Kanpur, on Drained Cathode Cell research Project. Finally, the authors would like to thank HINDALCO and ABSTCPL management for their support.

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