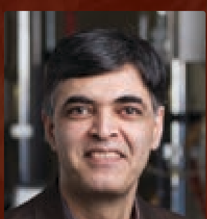
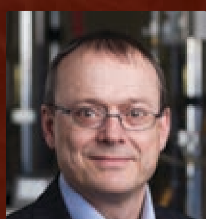
Energy efficiency in aluminium production

Professor Mario Fafard discusses how, along with his co-Princial Investigator **Professor Houshang Alamdari**, he is working to decrease the energy consumption in aluminium production and increase the lifespan of aluminium cell components





Could you outline the main objectives of your current Modelling of Aluminium Cell and Electrical Energy Efficiency (MACE³) project?

I hold the position of Industrial Research Chair (IRC) in MACE³. As the IRC, my duties are to facilitate the development of a basic understanding and subsequent modelling of the coupled phenomena that affect the lifetime and energy efficiency of the Hall-Héroult cell (the aluminium electrolytic cell). The modelling specifically involves the characterisation of materials and interfaces in extreme situations encountered in the cell or the anode production plant. Our main objective is to optimise the energy efficiency and lifespan of aluminium cells based on advanced modelling techniques.

The IRC programme is divided into three parts. The first part addresses a long-term objective: the advancement of knowledge in the modelling of complex phenomena and their numerical implementation. The second is an experimental support, which examines the thermo-electro-mechanical (TEM) behaviour on some parts of the cell, such as the anode. Finally, the third element targets projects where the behaviours of the TEM cell must be addressed in order to increase the energy efficiency and reduce greenhouse gas output of existing cells.

Why is it necessary to address the phenomena underlying the degradation of cells? How can these be predicted?

Degradation and lifespan predictions are significant fields of research connected to many industries such as aircraft motor parts, roads and bridges. To estimate and increase the lifespan of electrolytic cells, we must be able to understand the degradation process and set up realistic mathematical models of the phenomena, which induce degradation. In our case, we must take into account the migration of the ionic species inside the cathode block and try to model the main phase transformations, which induce its degradation.

With regard to cell modelling on the thermo-electro-mechanical aspects of a cell, what gap does your research fill?

It fills a huge gap! First of all, supposing we set up a complete model, taking into account all phenomena and simulates, from birth to death, the transient analysis of one cell, we will have to solve a numerical model which has possibly a billion unknown variables. It becomes a matter of computational power.

The second point is the uncertainty of the results. Two cells started at the same time and placed side by side could behave quite differently. The variability of material properties, the variation of these properties inside the cell, fluctuation in the movement of fluids and so on induce a kind of chaotic behaviour in the cell. Therefore, the results could be far from the reality. Nevertheless, modelling systems can help to understand the best ways to reduce energy consumption and increase lifespan.

MOLTEN CAST IRON

The largest gap, however, is the lack of exsiting knowledge to set up a global model. This is why we are using a step-by-step approach to build some parts of a global model, always taking into account the latest developments in numerical methods.

How has funding by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Aluminium Company of America (Alcoa) enabled you to further develop your project?

Without the NSERC and Alcoa, little would have been done over the last four years. To maintain a high quality of research, we need substantial funding to hire students and postdoctoral fellows. We must also support these students with a team of research engineers.

Scientific and technical support from the Alcoa is paramount to success within our projects. Alcoa management has supported us by assigning scientists to our R&D projects. We conduct regular meetings with representatives from smelters, the Alcoa Technical Center and Alcoa Global Primary Metals. Our team has also received strong support from the Aluminium Research Centre (REGAL) from Laval University.

There are a growing number of environmental and economic challenges facing industry. Will your research help to abate these issues?

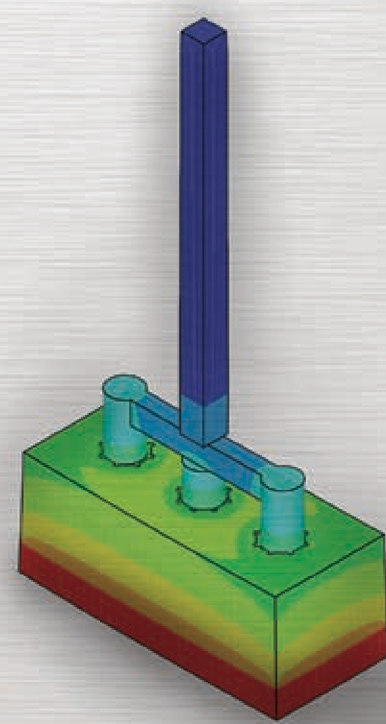
The worldwide situation of aluminium production is currently difficult due to its low market price. New challenges related to the supply of raw materials have also arisen, especially concerning the coke that is required to produce anodes. Thus, R&D projects with long- and short-term goals are crucial in helping the industry to face and overcome such challenges. This is why our strategy is to define different projects under the umbrella of the IRC, addressing the environmental and energy efficiency issues as they have direct economic impacts. We are preparing the renewal of the chair to be able to address more complex challenges.

Optimal **results**

The **Industrial Research Chair MACE^3** seeks to improve the energy efficiency of the industrial process of aluminium production to promote more sustainable practice. Its work to date holds great promise for its industrial partner

ALUMINIUM IS THE most abundant metal element in the Earth's crust and it is the second most widely used metal in product manufacture. However, it rarely occurs in its native state and the extraction of aluminium from ores is difficult. Aluminium production, therefore, relies on complex processes and requires a lot of energy.

The most common method of industrial aluminium production is called the Hall-Héroult process. Alumina (aluminium oxide) is dissolved in cryolite (sodium aluminium fluoride). It is then electrolysed in a cell that contains two carbon electrodes: a positively charged anode made from coke and a negatively charged graphite cathode. The coke reacts with the oxygen of alumina and is vented off as CO_2 while elemental aluminium settles to the bottom of the cell.



Thermo-electro-mechanical finite element analysis of an anode.

THE MACE^3 CHAIR

The Industrial Research Chair (IRC) Modelling of Aluminium Cells and Electrical Energy Efficiency (MACE^3) is a global research project that seeks to reduce the energy consumption of the Hall-Héroult process. The IRC is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Aluminium Company of America (Alcoa). It uses a combination of approaches to gain accurate information on aluminium electrolytic cell behaviour. These approaches include advanced modelling systems, advanced characterisation methods and the integrated development of numerical sensors.

MACE^3 is chaired by Professor Mario Fafard and his co-Principal Investigator Professor Houshang Alamdari. The programme aims to create a centre of excellence for studies on aluminium production, developing an understanding of the factors which affect the lifespan and energy efficiency of aluminium electrolysis cells. Its goal is to develop and implement advanced technologies, in order to mediate the environmental and economic challenges faced by the aluminium production industry. MACE^3 used the funding to conduct specialised experiments in laboratories, develop advanced modelling systems and train new scientists and researchers in material science, process engineering and computer modelling.

ADVANCEMENTS IN MODELLING SYSTEMS

The success of aluminium production relies on many different processes, including solid and fluid mechanics, heat transfer, electromagnetism and electrochemistry. Numerical modelling methods are the most effective way of understanding and estimating the outcomes of the complex relationships between these processes. Aluminium is produced at around 960 ºC and the temperature in the anode baking furnace is also very high (around 1,100 ºC). These high temperatures make it very difficult to obtain *in situ* measurements. Modelling techniques have therefore allowed the MACE^3 team to better understand the behaviour of the Hall-Héroult cell and the anode baking process, which in turn enables them to analyse and reduce electrolytic cell degradation and excessive energy consumption.

The MACE^3 researchers are employing two complementary modelling approaches to assess the behaviour of aluminium electrolytic cells. They use the existing Finite Element (FEM) code to model certain parts of the cell and to simulate the anode fabrication process. The group has also developed another FEM code called FESh++, which is able to perform advanced modelling of the cell by taking into account coupling between physical fields. By conducting tests based on advanced characterisation methods and modelling, they are able to produce increasingly accurate predictions.

THE MODELLING PROCESS

The systems employed by the MACE^3 researchers take into consideration the fundamental physical behaviours of the electrolytic cell components and the interactions between these components as well as the factors which affect them. Currently, they use laboratories equipped with specialised apparatus and unique bench tests, allowing for thermo-mechanical and thermo-electro-mechanical testing from room temperature up to 1,000 ºC. Using this technology, Fafard and Alamdari have been able to set up an advanced numerical model of the cell.

INTELLIGENCE

MODELLING OF ALUMINIUM CELL AND ELECTRICAL ENERGY EFFICIENCY (MACE[3])

OBJECTIVES

- To develop and maintain state-of-the-art technologies in order to overcome environmental, economical and competitiveness challenges in industry
- To improve the electrolytic cells' energy performance with a modelling/parameters identification/validation approach
- To develop basic knowledge on multiphysical-coupled phenomena affecting the cells' energy performance and lifespan
- To train highly qualified employees with a strong foundation in materials, process control and modelling

KEY COLLABORATORS

Laval University: **Professors Carl Duchesne**, Department of Chemical Engineering and **Louis Gosselin**, Department of Mechanical Engineering • Aluminium Research Centre – REGAL: **Drs Donald Picard** and **Patrice Goulet**, Research Engineer • Aluminium Company of America (Alcoa) Global Primary Metals, Technology, Innovation and Center of Excellence: **Dr Angelique N Adams**, Director, Global Technology Development; **Dr Donald P Ziegler**, Program Manager, Modeling; **Dr Jayson Tessier**, Senior Staff Engineer

FUNDING

Industrial Research Chair MACE[3], Natural Sciences and Engineering Research Council of Canada (NSERC), Alcoa and Laval University • Collaborative Research and Development Grant; Collaborative R&D Grant, NSERC and Alcoa • Research Program contributing to the reduction and sequestration of GHG, Research Fund of Quebec – Nature and Technology

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MARIO FAFARD is interested in the areas of advanced numerical modelling of aluminium cells and thermomechanical testing on refractory materials at high temperature, and is the founder of the Aluminium Research Centre – REGAL in the Province of Quebec, Canada.

HOUSHANG ALAMDARI has been working for over seven years in the nanomaterial and environmental catalysis industry, run several R&D projects, and developed a nanopowders production process by intense mechanical grinding with the conception and establishment of a pilot plant producing 30 tons per year.

UNIVERSITÉ LAVAL

MACE[3] MODELLING OF ALUMINIUM CELL AND ELECTRICAL ENERGY EFFICIENCY

The models work within certain sets of parameters, such as constitutive laws, which are able to simulate the behaviour of each individual component. These constitutive laws, based on fundamental principles (such as the second law of thermodynamics), are developed with specific variables that affect electrolytic cells. An exemplary variable is the baking index of the ramming paste. At the beginning of life of the cell, the paste is originally unable to sustain loads but during cell start-up it bakes and hardens. Thus, the baking index is used to follow the mechanical properties evolution of the paste.

The team also employs a simulation optimisation method to reduce energy consumption using sub-models. They calibrate the FEM models with existing measurements that have been obtained from scientists at Alcoa. Thereafter, they use those calibrated models to optimise the part of the analysed cell.

RESEARCH AND DEVELOPMENT PROJECTS

With the funding from the NSERC and Alcoa, the MACE[3] has had the opportunity to examine many different areas of aluminium production. The research has led to many projects, including Fafard and Professor Louis Gosselin's joint investigation into waste heat recovery and thermal integration in aluminium smelters, the reduction of energy consumption of the cathode collector bar and heat transfer analysis of the upper section of electrolytic cells. The researchers have also published papers documenting the benefit of using certain modelling systems to simulate sub-processes, such as the application of discrete element method (DEM) to the vibration process of coke particles.

Currently, IRC MACE[3] is trying to optimise smelting energy efficiency by reducing the pollutant emissions and energy consumption of aluminium smelting plants. This can be achieved by improving pre-baked anode manufacturing technology and monitoring the effect of anode quality upon the performance of smelting cells. The project also takes into consideration the energy consumption of manufacturing the anodes themselves.

The IRC has just received a grant for its new project, which is to develop a framework for quality control of the manufacture of baked carbon anodes by using modern multivariable analysis and non-destructive tests under the direction of Professor Carl Duchesne. They are trying to obtain funding from the NSERC CREATE programme to encourage collaborative and integrative approaches which address scientific challenges associated with aluminium production, and the funding will also facilitate the transition of new researchers from trainees to employees.

WORKING TOWARDS A GLOBAL MODEL

There is currently insufficient information about the physics behind electrolytic cells to set up a global modelling system. However, the researchers at MACE[3] are working on optimising energy consumption within as many sub-processes as possible. They work with incomplete models to obtain practical results whilst simultaneously developing and perfecting them. An example of their work includes a PhD student who is building 3D models of the anode-baking furnace to optimise the baking process, while another model simulates the anode shaping process. The combination of these two simulations will ultimately enable the anodes to obtain a constant density, thereby increasing energy efficiency.

By using an incremental approach to contribute towards a global model and by constantly updating their systems according to new developments in numerical modelling, MACE[3] will soon be able to optimise the energy efficiency and lifespan of Hall-Héroult cell components. In turn, this will have a positive impact upon the environmental and monetary costs associated with the industrial production of aluminium.

Graduate student preparing a real size test on anode.
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