COOPERATIVE REFRACTORY RESEARCH PROGRAMMES TO SUPPORT REFRACTORIES DEVELOPMENT

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ABSTRACT
The Federation for International Refractory Research and Education (FIRE) is a non-profit organization established to promote refractory related research and education on a global basis. FIRE aims to stimulate and reinforce international education and research programmes for the refractory industry. Its strength is a unique grouping of expertise drawn from all sectors of the refractory producing, supplying and consuming industries coupled with the world's leading academic institutions involved in refractory research. FIRE is committed to a series of research programmes which are by definition pre-competitive and are aimed at leveraging the research network capability of FIRE with contributions from both industrial and academic partners. They are designed to further refractory science and provide a basis for education through academic research.

As an illustration of how cooperative research programmes can benefit the development of monolithic refractories, a data mining analysis of published papers spanning a more than 20 year history has been used to identify different active communities and the fields of research around refractories on a global basis. The importance of the FIRE network and the establishment of different research communities can be seen emerging in recent years.

More specifically, the analysis provides a linkage between the different global research communities and research themes relevant to refractories. The paper will illustrate some of the ongoing cooperative programmes in the field of refractories research and how different disciplines can be harnessed to yield new and novel insights into the underpinning mechanisms of refractories technology.

Conclusions will be drawn from the key learnings of these multi-partner research programmes and how this can be applied to create further value through the usage chain of refractories. Future perspectives will explore the areas where further basic cooperative research on monolithic refractories could bring benefits.

INTRODUCTION

The Federation for International Refractory Research and Education [1,2] is a non-profit organization established to promote refractory related research and education on a global basis. FIRE aims to stimulate and reinforce international education and research programmes for the refractory industry. Its strength is a unique grouping of expertise with 27 members drawn from all sectors of the refractory producing, supplying and consuming industries coupled with the world's leading academic institutions involved in refractory research. FIRE is committed to a series of research programmes which are by definition pre-competitive and are aimed at leveraging the research network capability of FIRE with contributions from both industrial and academic partners. They are designed to further refractory science and provide a basis for education through academic research.

The challenges today are to educate refractory engineers who are able to conceive, design, implement and operate complex, value-added refractory products to optimize the entire refractory life cycle (including recycling). It is also essential to recognize that those young engineers will be called to work in an international team-based environment, hence will have to be trained to develop not only a working knowledge of technical fundamentals but also will have to learn and develop personal and interpersonal skills. As Dr. Lynn McAlpine from Oxford University in the UK comments [3,4], the educational goal to achieve this ambition, via a curriculum would ideally involve a team with varied subject matter expertise, including industrialists in refractory mining; academics in mineralogy, metallurgy and ceramics; specialists in organizational behavior as regards interpersonal communication; and educationalists. FIRE with its unique multi-cultural and multi-disciplinary composition is able to exactly draw on these skills and provide a unique framework for furthering refractory education within the context of multi partner research programmes. FIRE aims to promote higher education in refractory materials engineering, fulfill the cultural, educational and research related needs of the refractories industry to provide conditions in order to graduate global player professionals and finally to carry out pre-competitive research which is an important tool for FIRE's student education. The analysis show the value of partnership based research with a significant contribution to refractory knowledge being made across all the dimensions of refractory research. FIRE represents a unique opportunity for pre-competitive consortium based refractory research whilst at the same time providing an educational framework for post-graduate students.

- For the industrial partners the leveraged benefits of state of the art research by the world's leading universities are clear with a multiple of research funding being typically more than 4 for every euro invested. In addition, the programmes contribute to the education of the next generation of refractory technologists and researchers who are primed for international careers.

- The academic partners benefit through an access to complimentary expertise in the world's leading universities to expand research capacities and the ability to attract and educate students of a high quality for MSc and PhD programmes

It is important to be mindful that students developing the research in FIRE are enrolled in the MSc and PhD programs and in order to be trained, evolve scientifically and to promote FIRE, they need to publish part of their results. UNITECR meetings present an excellent forum for FIRE students to demonstrate part of their research as a means of furthering refractory knowledge. This can be seen by the contribution of FIRE previous Unitecr programmes with generally more than15 papers being presented as a result of FIRE research programmes which by itself would attest the quality of the results and the good educational level attained.

Recently, a map of global refractories research has been published to understand its temporal macroscopic trends [5]. Moreira et al showed that by using the data mining technique based on the Scopus database patterns can be revealed about a certain topic of interest within refractories. It provides a complete macroscopic map of the research and trends, enabling us to differentiate clusters and networks that are currently active in the refractory field. This provides insights into the evolution of refractory technology, as well as detect trends that are currently being developed. This paper discusses the links established in this data mining analysis and the FIRE organization and how cooperative research programmes can benefit research and subsequent refractories developments.

DATA MINING OF REFRACTORIES

By using data mining and graph analysis, established methodology, a complex refractory field Network can be constructed and classified providing information and trends from different levels of its structure (macro to Nano). It can disclose temporal trends and connections on the available data extracted from data mining of scientific and technical publications.

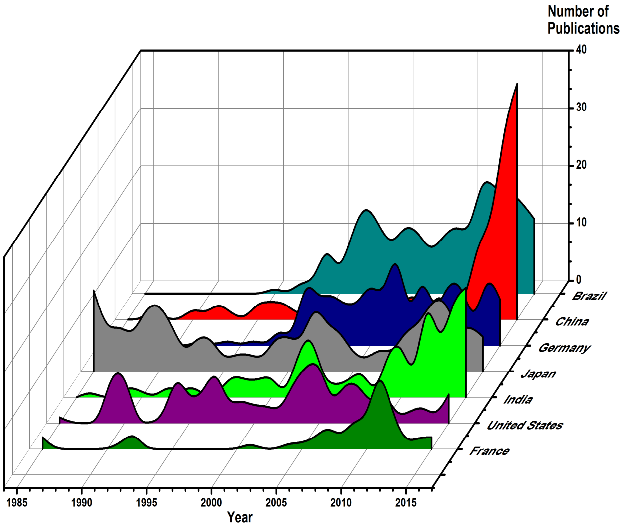

Fig. 1: Evolution of the number of refractory publications from selected countries [5]

As can be seen in Figure 1, there is a major rising trend in the number of publications over the whole period analyzed. It can be observed that for shorter segments of time (1-4 years), the data do not present a real trend and are close to a random behavior, as economic and political factors might directly affect the scientific production. It can be pointed out that Japan and the United States were the dominant players in the number of publications in the late 1980s. After 1995, their production reached a plateau whereas all the other countries started to slowly increase their participation. In 2010, the scientific production of China rose dramatically, leading by far the number of papers published in 2015. This sudden increase is related to its economic growth in the past decade and massive government investment in education, research and development. The number of publications alone is not a strong indicative of the technological importance of each country as the journals used to retrieve the publication data present different impact factors. The cumulative impact factor (CIF) measures how often its papers or reviews are quoted by other publications, i.e., it is a measure of its importance. Therefore, CIF is a stronger indicative of the technological importance of each country in the refractory area. When comparing data from the number of publications together with the CIF (Fig 2) it can be observed that countries with a higher number of publications are usually the ones with a higher CIF. Japan is an exception, as most of the Japanese papers were published in the TARJ journal which is not an indexed journal. Furthermore, most of the TARJ publications were not co-authored in collaboration with foreign researchers. The analysis also shows that countries with a higher number of publications are usually those with a higher degree of collaboration. Furthermore, these results show that although Germany has a large number of international partnerships concerning research, its CIF value is not very high, which is related to the journal selected for publication. On the other hand, Japan stands out as the country with the lowest degree of collaboration among those with a number of publications higher than 100. It is important to mention again the influence of TARJ publications, where most of them involve only Japanese authors. The countries that take part in international collaboration play different roles in the partnerships. To measure the degree of importance or leadership of each country in the international collaboration scenario, Figure 3 presents the betweenness centrality ($C_b(n)$) versus the number of publications. $C_b(n)$ indicates the importance of a specific country in the network as it accounts for the density of connection that each country presents. Therefore, countries with high betweenness centrality are more likely to act as a bridge, as authors with affiliations in such countries have a greater probability of working with authors of different ones and develop new collaborations among themselves. Hence, countries which have high $C_b(n)$ act as agents to induce refractory research.

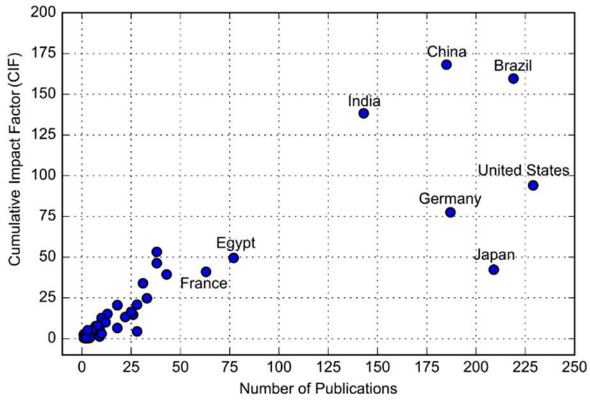

Fig. 2. Cumulative Impact Factor (CIF) and Number of Publications of each country from 1985 to 2015

The United States presents the highest betweenness centrality, which points out their leading role regarding publications and collaborations with different communities. On the other hand, Japan has the lowest $C_b(n)$ value among the countries with more than 50 publications. This is also related to the fact to the previously mentioned factor that most publications from the JTARJ database do not have international collaborators.

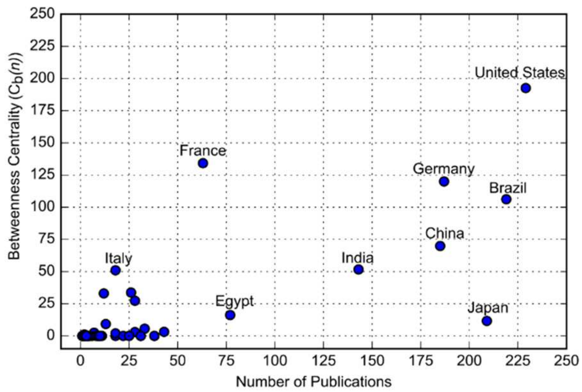

Fig. 3. Betweenness Centrality [$C_b(n)$] and Number of Publications of each country from 1985 to 2015 [1]

Another important aspect arises when analyzing France. Although its number of publications is lower than seven of other nations, it has a high betweenness centrality [$C_b(n)$], highlighting its high degree of collaboration and also interaction with a wide range of countries (from different communities). Furthermore, all the countries with a high CIF present a high degree of collaboration (*D*) and a high $C_b(n)$, which shows that these countries are leaders in their respective communities.

These results also indicate an important feature of programs that motivates international collaboration such as the Federation for International Refractory Research and Education (FIRE). The five countries with the highest $C_b(n)$ (United States, France, Germany, Brazil, China, in descending order) are academic and/or industrial partners of FIRE. This is explored further in Figure 4 which shows the impact of the FIRE network on papers published within the countries where FIRE is active. In order to understand the evolution of the leading countries in more depth, the database was divided into 4 time period from 1985 to 2016 for the United States, France, Germany, Brazil, China and Japan. There is a discernable clear rising trend of the degree of collaboration which started in the early 2000s.

This behavior matches with the beginning of FIRE, which was created in 2005, as the *D* values of all countries involved with the Federation started rising after the third period – 2001 to 2008 - (even for the USA and Japan scenarios where there was a drop in the late 1990s and early 2000s). This increase in cooperation is also reflected in the Betweenness Centrality [$C_b(n)$]. The rise of $C_b(n)$ points out the increasing importance of these countries in international collaboration in the refractory research field. The presence of FIRE partners in these countries indicates the impact of this organization, which is also strengthened by the high values of the CIF (Figure 4) and the number of published works by these countries.

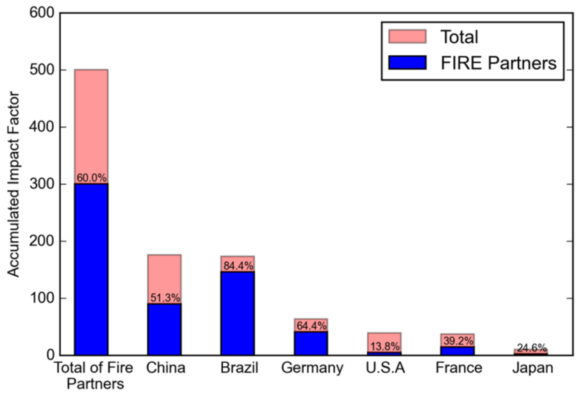

Fig. 4. Impact Factor of selected countries publications relative to the weighting of papers produced within the FIRE network

Data mining has given an insight into different research networks and their research topics but it also detects early trends via examining trends in published papers and their contents via key words. Closer collaborations, on one hand, between materials science and natural sciences and, on the other hand, between materials sciences and engineering disciplines are vital in order to accomplish significant advances in refractory research. Interesting technology trends can be clearly elucidated and the next section shows the alignment of FIRE research programmes to these trends and research themes.

COOPERATIVE RESEARCH PROGRAMMES

In terms of subjects the data mining analysis [5] indicated highlighted the following themes of importance in terms of collaborative research in the field of refractories;

- Synthetic high purity raw materials. For example, alumina, zirconia and mullite. The strong link between alumina and zirconia shows the extensive research carried out on alumina toughened zirconia (ATZ) in the late 1980s. Another strong connection links magnesia and carbon reinforcing the high production and importance of MgO-C refractories in primary and secondary steel making.
- Bonding systems with calcium aluminates being the most dominant but emerging research in the field of other types such as phosphate and colloid bonding– known for long time but maybe not present referenced research
- Development of new Testing and characterization methods to closer approach actual usage constraints in the form of ;
    - Rheology of monolithic refractory systems
    - Processing aspects of refractories and particular placing properties of monolithics
    - Thermal shock
- Developing Simulation tools particularly in the field of thermo-mechanical behavior. Integration of basic science, thermodynamic and thermomechanical simulation are fundamental to design advanced refractories. While taking care to run pre-testing evaluations that would better correlate the application with the real environment of the product. This leads to the view that refractory research is moving towards developing more modelling tools and the ability to characterize refractory materials under multiple constraints to better simulate actual conditions of use to better predict wear.

To accompany the Education programs in Refractory Science and Engineering, FIRE is involved in specific research ones with multiple FIRE partners [6]. These researches are pre-competitive refractory projects that are the responsibility of an academic FIRE member, with contributions from other members to promote international networking. All of the research projects involve the participation of selected FIRE students as well the research staff attached to the refractory labs. Project funding are sought from FIRE, government agencies, industry and internal funds from the participating universities. To date two research cycles have been completed on a wide array of cooperative subjects. The important element is the cooperative networks where different academic institutes are involved for each theme along with a range of industrial partners. The first cycle of research programs for the 2008-2015 period was focused around three pillars;

- Thermo-mechanical behavior of refractories, modelling and testing
- Design of cement bonded refractories
- Thermo-chemical behavior of refractories, modelling and corrosion testing

FIRE has coordinated these research basic research programmes and thanks to the network contribution of both academic and industrial partners a number of common transversal themes can be gleaned from these programmes illustrating then benefits of collaborative research to stimulate refractories development. For example [7], within the field of ladle refractories these above mentioned research programme provide elements to understand the complex thermo-mechanical, thermo-chemical interactions along with a greater understanding of the impact of material properties and their combination on performance in use. The research programmes gave insight into three areas of fundamental importance for ladle refractories where value can be brought through reduced downtime and increased durability/ in service life. The results relied on a combination of modelling, simulation and measurement to demonstrate how research can bring value to the usage chain of steel ladle refractories. The three aspects of the thermo mechanical behavior of refractories, modelling and testing, the design of microstructurally engineered corrosion resistant castables and an approach to determine the thermochemical behavior of refractories from the perspective of modelling and corrosion testing showed;

- The link between lining configurations and thermo-mechanical behavior is examined to answer the question of how the steel ladle insulation layer influences the thermal and mechanical behavior and what are the design parameters.
- Results from thermo-chemical studies of the corrosion resistance of magnesia containing refractories for steel ladles showed a good agreement between thermodynamic modelling and post-mortem analysis of used refractories. The quantification of the corroded phase via an appreciation of the mechanisms is now possible
- It is well known that the production of a high performance in-situ spinel castable is not straightforward. In order to add magnesia in a castable, processing difficulties, such as fast flow decay and mechanical damages related to magnesia hydration have to be managed as well as their impact on installed properties. A second challenge is how to manage the spinel and CA_6 formation. Results showed the influence of the matrix raw materials and additives in attaining an engineered microstructure.

The current series of network based cooperative programmes running from 2015 illustrate further how collaborative research can contribute to refractory development;

- Insulating refractories and their applications in multilayer lining designs
- Energy efficient refractories: a holistic approach based on fundamentals, processing and evaluation
- Liquid phase and vapor phase corrosion: new methodologies and new cases of corrosion
- Dense refractories with enhanced flexibility

The key learnings of these multi-partner research programmes address critical issues such as the conservation of energy expressed either through the intrinsic content of energy in refractories or their insulation function to save energy coupled with the notion of greater sustainability by designing refractories that last longer and consume less resources. Over and above the material benefits of collaborative research on refractories development values can be derived for both academic and industrial partners of FIRE. For the industrial partners the leveraged benefits of state of the art research is around a multiple of research funding being typically more than 4 for every euro invested. In addition, the programmes contribute to the education of the next generation of refractory technologists and researchers who are primed for international careers to promote technology development of monolithics.

The academic partners benefit through access to complimentary expertise in the world's leading universities to expand research capacities. On top of this is the ability to attract and educate students of a high quality for MSc and PhD programmes

CONCLUSIONS

FIRE is an outsourcing network with today some 27 partners, in 10 academic institutions, in 8 countries supported by 17 industrial companies from 11 different countries distributed over 4 continents.
To train efficient refractory engineers, FIRE refractory educators have created an environment where the students are able to learn materials and refractory technology in an economical, ecological and ethical context, much broader than it was the case previously, in order to understand the business and the cultural issues the industry is facing. To cope with so many challenges, new forms of collaboration between the academics themselves and between the refractory industrialists and academics have been invented. Outsourcing has also been introduced in the academic world, to keep the costs of education at a level where it can be attractive to recruit graduate students and to follow a more systematic approach to pool the resources and the expertise more efficiently to find complementarities, in teaching as well as in research.
Fire's long term objectives will remain to contribute to the education and assimilation of knowledge, with wisdom to the benefit of all players, in the chain of values along the global life cycle of refractories, absolutely essential to industrial life.

This paper has shown how powerful data mining and graph analysis can be to detect trends within a given industry sector and identify different research networks and scientific communities. The analysis provided a link between the different global research communities and important topics for the refractory area such as raw materials, binders, mechanical tests and simulations. By analyzing the published data, ongoing cooperative programmes in the field of refractories have been identified and how different topics can be associated to induce novel insights. Interesting technology trends can be clearly shown through data mining.

Refractory technology and scientific knowledge trends is a complex area, which requires the cooperation of different skills and expertise. Networks are more powerful than individuals regarding research effectiveness. As an example, the FIRE network is a major illustration of the leveraging that can be achieved to advance fundamental refractory technology via the association of the world leading academics in refractory science. These cooperative efforts and their quality can be identified, as shown by the high average impact factor analysis attained by the communities in this network. It is believed that these multi-partner research programs must be promoted to create further value through the usage chain of refractories.

The motivation to continue developing refractory bond systems remains as strong as ever. The emergence of novel binders in niche applications and the continuing use of hydraulically bonded refractory products will be stronger in the near future. These developments will surely fuel the growth of refractory castables and their potential replacement for other kinds of refractories, mainly the pre-fired ones;

Future perspectives, where basic cooperative research on refractories could bring further benefits, will involve integrating basic science as well as thermodynamic and thermomechanical simulations, which are fundamental to design advanced refractories. In parallel, running pre-testing evaluations that could better correlate the application with the actual working environment of the product would also be required. Although not yet pointed out by the survey, additive manufacturing is a potential technology disruption that might change the refractories area.

The analysis of different testing and characterization techniques showed that refractory research is moving towards developing more modelling tools. Furthermore, the ability and capability to characterize refractory materials under multiple constraints in order to better simulate actual conditions of use will also be required.

ACKNOWLEDGEMENTS

Acknowledgments are given to all FIRE academics, students and alumni who have made contributions to the FIRE programs and kept the FIRE burning. In particular, grateful thanks are given to the Sao Carlos Academic group led by Prof. V. C. Pandolfelli without whom this paper would have not been possible.

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