A BOOST IN RESEARCH ON SLAGS: A DOUBLING IN PUBLICATIONS FROM LITERATURE SINCE 2003

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ABSTRACT

Starting in 1997 with the 5th International Conference on Slags and Fluxes a survey on research on slags has been done preceding the next conference on slags and fluxes. Trends from 1980, the year of the first conference in Halifax, Canada, have been traced and discussed.

In the present paper the recent trends in slag-related research from 2004 to 2007 is analysed in terms of:

- *Annual publication rate*
- *Geographical origin of the work*
- *Nature of the research (e.g. thermodynamics, kinetics)*
- *Nature of the slag studied.*

Earlier study has revealed that in the beginning of the new millennium a publication rate of 1 paper on slags per day was produced world wide. From the new survey it is found that since 2003 the number of publications has increased remarkably, leading to a doubling in 2006 equivalent to two papers on slags published per day world wide. The underlying mechanism of this increase is presented and discussed. There has been a significant increase in recent years on the amount of work carried out on the recycling and environmental aspects of slag in recent years.

INTRODUCTION

In 1996 we reviewed [1] papers on slags and fluxes published in the period from the First (1980) to the Fifth (1997) International Conference on Molten Slags and Fluxes. On the occasion of the 6th International Conference on Molten Slags, Fluxes and Salts, held in Stockholm and Helsinki in June 2000, we analysed further the developments from 1996 to 2000 [2, 3]. The review on slags and fluxes from published literature was continued to be presented at the VII International Conference on Molten Slags, Fluxes and Salts, held 25-28 January 2004 at Cape Town, South Africa [4, 5]. The contributions to this conference were analysed based upon the titles and abstracts available from the preliminary programme and compared with the trend in literature.

In this paper we have used the same methodology to detect the trend in research on slags and fluxes entering the new millennium as done in the foregoing publications. The results for the years 2004-2007 and data available for 2008, by definition incomplete at the time of writing this paper, were studied following the established methodology. Earlier analysis results are taken into account starting with 1999. A comparison is made of these results with the analysis of the preliminary programme of the VIII International Conference on Molten Slags, Fluxes and Salts, scheduled for 18-21 January, 2009, in Santiago, Chile.

METHODOLOGY

Based upon the METADEX reference source for metals a literature survey was produced using the key words *slag, mould flux, casting powder and matte as descriptors*. We did not use the descriptor *salts* to be able to compare the results of the actual study with the earlier published work. The abstracts of the papers as a result of this query were then used to identify the nature of the research investigation, the type of slags studied and the geographical origin of the research groups involved.

In Table 1 the total number of abstracts per year is collected identified by the query performed in January 2004 (just before the beginning of the VII International Conference on Molten Slags, Fluxes and Salts in Cape Town) as well as the results achieved in the present study in 2008.

Table 1: Annual number of slag-related papers from the METADEX reference source 1980 to 2008. For the period 1980-2003 the survey made in 2004 is compared with that in 2008

Year	2003	2008	Year	2003	2008	Year	2003	2008
1980	356	382	1990	347	355	2000	454	483
1981	338	378	1991	367	367	2001	425	461
1982	367	403	1992	393	413	2002	474	475
1983	394	410	1993	410	404	2003	498	575
1984	409	427	1994	350	370	2004	142*	661
1985	444	432	1995	330	352	2005		648
1986	460	460	1996	312	330	2006		765
1987	428	432	1997	339	363	2007		660
1988	459	459	1998	347	375	2008		165°
1989	431	452	1999	371	412			

* Survey results to January 2004; Survey results to July 2008

In Figure 1 the two data sets are compared. It is clear that the METADEX reference source has been updated with historical material over the last five years. From the 2000 search an average annual production of 348 papers was found, a number that increased to 387

from the 2004 search. In 2008 the average is increased to a level of 454 over a period of 28 years (2008 excluded due to incomplete data).

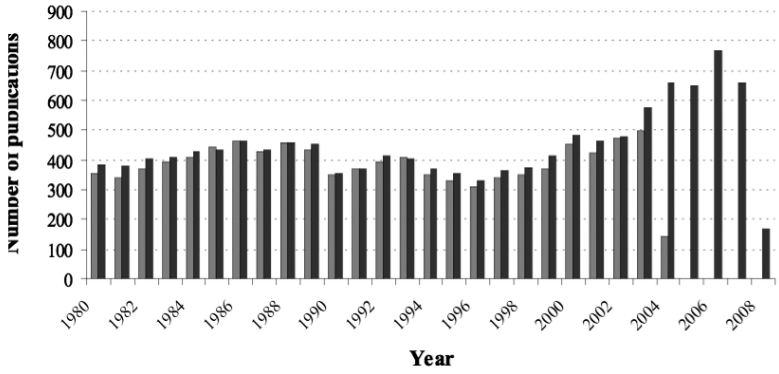

Figure 1: Number of slag-related publications from METADEX resulted from searches in 2004 and 2008

If we just take the results of the years 2000-2007 then the average publication number equals 579 per year. One can conclude that the worldwide publication rate for papers on slags, fluxes and mattes in the new millennium equals 2 per working day (excluding Sundays).

Geographical Origin

The geographical origin is classified according to the following global partition: United States of America (USA), Canada, Japan, European Union, Russia, Eastern Europe, China, Korea, India, Australia, Central & South America, South Africa and Others (including Taiwan). The percentage of papers per geographical area is collected in Table 2 and presented in Figure 2.

The geographical origin has changed drastically over the period 2004-2008, this in contrast to earlier reviews where the picture remained remarkably stable. Russia used to be the most productive country in slag-related publications with about a quarter of the total every year. The relative contribution of Russia has dropped with a factor ten from 24% in 2004 to 2.3% in 2007 for which we do not have an explanation. China has grown impressively, to a level of more than one third of the slag-related publications [6]. This is in line with the ultra-fast growth of the metallurgical industry in China, especially the iron-and steel industry. Steel production in China in 2007 is reported as 490 million tonnes out of a world total of 1344 million tonnes [7], or 36%. This is remarkably similar to the Chinese share in slag-related publications over 2007 that equals 36.8% (Table 2). Although the growth rates of the BGP of China and India are comparable, the publication rate of India lags far behind China. A clear increase in relative contribution of India can not be noticed.

Since the last review the European Union has enlarged in two steps from 15 member states to a total of 27 member states. Important metal producing countries such as Czech Republic, Hungary, Poland, Slovakia and Slovenia joined the EU in 2004 followed by Bulgaria and Rumania in 2007, thus all in the period covered by the actual survey. This explains the reduction in papers from Eastern Europe and the increase in relative importance of the European Union publications. The contribution from Japan has been stable in percentage even with an increase in total of publications.

Some authors are difficult to place, where undecided their paper has been attributed to

the country of publication of which the USA may have benefited from. The level of USA publications on slags and fluxes is relatively low.

Table 2: Geographical origin of research on slags (%), data for 1999-2003 from [1, 2, 3, 4, 5]

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
USA	8.9	8.1	7.0	8.7	2.1	9.5	6.4	5.1	6.4	2.6
Canada	3.9	5.1	4.4	3.9	4.3	4.1	4.7	3.3	1.7	1.6
Japan	10.2	11.2	14.0	13.1	6.4	14.0	11.0	10.6	10.2	13.4
European Union	12.7	7.4	11.4	9.0	12.8	16.2	14.9	18.8	18.0	13.7
Russia	31.3	28.9	24.9	24.9	40.4	24.0	7.2	3.5	2.3	2.3
Eastern Europe	4.4	4.7	5.8	6.4	2.1	2.8	2.2	2.7	3.1	1.6
China	11.9	19.0	17.1	11.8	8.5	10.3	28.6	36.8	41.3	37.3
Korea	5.3	3.8	3.6	6.9	4.3	2.8	1.7	2.5	2.7	2.6
India	1.9	1.8	2.2	1.5	8.5	4.1	5.3	2.3	4.2	2.6
Australia	1.9	4.0	3.9	4.9	4.3	3.2	3.3	2.8	3.1	2.6
Cent/South America	4.7	2.9	4.3	4.1	4.3	6.1	11.7	6.5	2.3	14.7
South Africa	1.4	1.6	0.5	2.6	0.0	0.7	0.6	1.4	0.6	0.7
Others	1.4	1.6	1.0	2.1	2.1	2.2	2.4	3.7	4.1	4.3

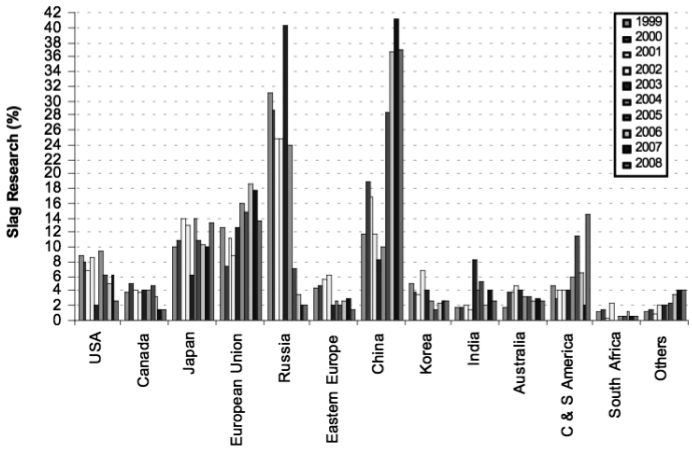

Figure 2: Geographical origin of slag-related papers in period 1999 to 2003

Nature of Research Activities

The nature of the research activities on slags, fluxes and mattes is distinguished in: phase equilibrium or mineralogical studies, thermodynamics, kinetics, physical properties, slag/metal equilibrium, the combination of plant data and process modelling, refractory erosion, foaming and smelting reduction, modified oxygen steelmaking, slag splashing and the combination of environmental and recycling studies. The percentages are collected in Table 3 and presented in Figure 3.

Table 3: Distribution of slag related research activities (%), data for 1979-2003 from [1, 2, 3, 4, 5]

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Phase equilibrium mineralogical	5.4	4.6	4.1	4.5	2.3	7.3	2.0	4.4	3.4	2.3
Thermodynamics	5.4	8.4	6.9	7.5	2.3	7.1	8.2	4.2	4.0	5.0

Kinetics	7.6	7.9	3.7	4.3	4.5	5.6	3.3	2.3	2.7	2.0
Physical properties	9.5	11.5	9.7	9.0	2.3	5.9	7.0	5.8	6.5	5.6
Slag/metal equilibrium	14.1	8.4	8.3	12.3	20.5	10.1	8.8	9.6	7.6	6.0
Plant data/ process modelling	37.8	38.6	44.1	37.6	34.1	39.5	39.0	38.0	37.4	36.4
Refractory erosion	2.4	1.8	3.0	3.3	2.3	4.4	8.9	12.6	13.4	11.3
Foaming/smelting reduction	4.6	4.9	3.7	3.3	2.3	1.9	1.2	1.1	1.5	1.7
Modified oxygen steelmaking	0.3	0.4	0.2	0.3	0.0	0.7	0	0.3	1.0	0
Slag splashing	1.6	2.9	1.6	1.5	2.3	1.0	1.9	0.8	0.8	0
Recycling/ environmental	11.1	10.4	14.7	16.5	27.3	16.5	19.7	20.9	21.7	29.7

The great majority of published works of almost 40 per cent is devoted to plant data and/ or process modelling, as was the case in the foregoing survey. Plant data/process modelling is a catch all category which includes a wide spectrum of activities such as plant data, mathematical and physical modelling, sensors and equipment, and chemical analysis.

The re-use of slags in cements is distorting the review and this level is increasing over time. From the research it appears that blast furnace and fly ash (coal slag) improve the quality of cements and they are the preferred materials now for cement making. As cement production is one of the big contributors to the greenhouse gases much attention is paid on development of energy-saving and thus lowering CO_2 emission. Increased use of slags as raw material for cement production will lower the CO_2-emission of this important industry. About 80% of the slag-related publications under the heading *Recycling/ environmental* relate to cements with the other 20% on re-use in steelmaking processes, ceramics, absorbents for gases and the like. Developments are ongoing to use steelmaking slag for cement production but it has still got to achieve more in cements before it is the preferred material. The principal use of steelmaking slag is as an aggregate in road-building or dike filling but it has also been used for ceramics as filler material.

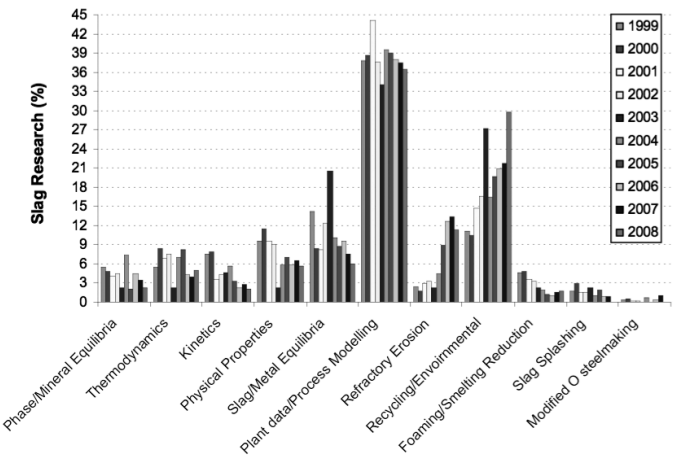

Figure 3: Research activities of slags investigated in the period 1999 – 2008

In 2008 the Recycling references almost equal the plant and process data category- showing the extent of the distortion one hand and the increased attention for environment in general. Most refractory –based publications have been classified under refractory erosion even if they refer to mechanical properties of refractory.

The decreasing number of slag/metal equilibria studies, noted previously [4, 5], seems to

be a continuing trend. Appreciably more has been published about refractory erosion and slags in 2005-2008 than in the periods before. The percentage of publications on slag foaming and smelting reduction has become rather stable after a period of continued decrease. Only a few papers are dedicated on slags for modified oxygen steelmaking since 2004.

Types of Slags studied

The results of the analysis, in terms of types of slags studied, are presented in Table 4 and Figure 4. About a quarter of all slags studied since 2003 is directly related to the steelmaking process which is a prolongation of the earlier reported trend. The relative occurrence of studies of ironmaking slags has been doubled since the last review, which might be explained by the shortage of high-grade raw materials for the Blast Furnace. The ironmakers have to rely on lower grade input iron ore, coking coal and injection coal which has a direct influence on the ratio slag/hot metal and the composition of the slag, as well as to the pressure to reduce CO_2 emissions in ironmaking. An increase is also noticed in ladle and refining slag studies. If we add the average percentages over the years 2004-2008 for ironmaking slags (23%), steelmaking slags (25%), ladle/refining slags (15%) and the mould fluxes for continuous casting of steel (5%) we can conclude that more than 68% or two-third of all slags studied are directly related to industrial iron- and steelmaking. This is surprisingly more than the 50 % that was found in the preceding review [4, 5]. We stated at the time that: *Compared to the relative importance of iron and steel in the international metals world this fraction of 50% should be much higher. Given the long human experience with iron, (more than an Iron Age or 3000 years) the knowledge of iron- and steelmaking slags will eventually come to certain saturation. The knowledge on processing of the new non-ferrous metals on the other hand needs to be extended and deepened, which explains the steady increase in non-ferrous slag studies*. Indeed the fraction of iron- and steel-related slag studies has increased as has the total volume of steel produced world wide. However, the number of slag studies for non-ferrous materials has decreased, contrary to our expectations.

The cement references swell the two categories of *Ironmaking and Coal slags*. Where slag wastes are used as source of certain metals these have been usually categorised as *Recycling/environmental* but some may have been classified as *Plant data/process modelling*. Virtually all *Coal slags* refer to use in cements, only 1 or 2 per year are on coal gasification. *Wastes* refer principally to recycling dusts and also to slags produced by combustion of sewage and other wastes in Municipal Waste Incinerators. The entry *Synthetic slags* covers laboratory studies and thermodynamic calculations on slag systems.

Table 4: Type of slags and fluxes investigated (%), data for 1999-2003 from [1, 2, 3, 4, 5]

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Ironmaking	9.1	12.6	12.2	11.1	15.9	7.1	23.8	20.3	23.9	23.9
Steelmaking	25.3	20.3	22.0	28.1	22.7	30.7	23.7	18.3	23.8	26.0
Ladle/refining	8.0	7.7	13.6	10.1	6.8	14.1	12.6	19.6	15.5	13.9
Mould fluxes	6.6	7.0	6.8	3.7	0.0	2.9	7.2	5.2	5.6	3.9
Welding fluxes	1.1	1.3	0.9	0.5	2.3	1.2	1.1	3.3	3.7	2.4
Non-ferrous	12.1	15.4	13.1	18.5	36.4	2.9	12.1	10.6	7.1	8.8
Mattes	13.2	10.1	9.8	7.9	4.5	15.3	3.5	6.3	1.5	2.7
Synthetic	17.9	18.7	14.5	11.1	6.8	17.9	9.0	7.5	7.5	6.1
Ferro alloys	3.8	3.3	1.4	3.0	4.5	4.7	2.3	2.5	0.2	2.7
Wastes	3.0	3.5	5.6	6.2	0.0	2.0	1.7	2.4	3.9	3.0
Coal	-	-	-	-	-	1.2	3.0	4.0	7.3	6.6

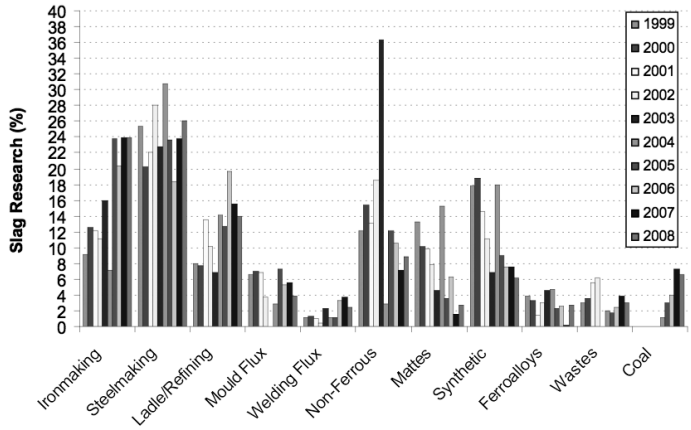

Figure 4: Type of slags studied in the period 1999 - 2008

Review of Conference Proceedings and Programmes

Previous reviews [1, 2, 3, 4, 5] showed that the conference proceeding publications are not a true reflection of the research activity on a global basis because they are strongly influenced by both geographical and economic factors. We analysed the contribution to the VIII International Conference on Molten Slags, Fluxes and Salts MOLTEN2009, to be held in Santiago, Chile, South America, from the overview of papers made available for referees in the middle of August 2008. The results presented in Table 5 and Figure 5 show that historically there is a marked distortion in attendance for the host country and neighbouring countries. However, for the case of MOLTEN2009 there is only a slight increase of contributions from South and Central America as compared to historical data. EU participation has been announced at a remarkably high level of around 30% which is much higher than the 16 to 19% publication share over the last 4 years. Japanese participation in the conference is higher than in the 2004 conference, whereby the downward trend that started with the Stockholm/Helsinki conference has been stopped. The Japanese contribution to MOLTEN2009 is in accordance with the Japanese rate of publications on slags and fluxes. The participation of China is the highest ever in the history of the Molten Slags and Fluxes Conference series, in accordance with the increasing importance of Chinese research on slags and fluxes. There are two Russian papers announced bringing the Russian participation to a very low level of 1.3%. Both USA and Canada are better represented at Chile than at Stockholm/Helsinki and Cape Town.

Table 5: Geographical origin of papers published in Conference Proceedings or Programmes (%), data for 1979-2004 from [1, 2, 3, 4, 5]

	1980	1984	1988	1992	1997	2000	2004	2009
USA	13.0	*28.6	10.1	4.8	8.6	5.6	4.1	6.5
Canada	*24.0	14.3	7.6	3.2	2.0	0.9	5.4	8.4
Japan	20.4	26.0	34.4	*50.8	34.3	16.9	8.8	11.0
European Union	29.6	15.6	*36.9	17.7	12.5	*30.5	36.4	28.3
Russia	5.6	0.0	0.0	7.4	2.5	13.4	2.7	1.3
Eastern Europe	0.0	1.3	0.0	1.6	0.0	4.6	2.7	5.2
China	1.9	2.6	0.0	6.5	4.9	11.6	5.4	13.5

Korea	0.0	0.0	0.0	4.0	4.9	3.0	5.4	5.8
India	1.7	1.3	1.3	0.0	0.0	2.0	2.0	1.3
Australia	1.9	5.1	5.2	3.2	*22.5	5.2	14.9	9.7
C&S America	0.0	5.2	5.2	0.0	2.0	3.5	3.4	*4.5
South Africa	1.9	0.0	0.0	0.8	4.9	2.2	*7.4	3.2
Others	0.0	0.0	0.0	0.0	1.0	0.7	1.4	1.3
Place slag conference	Halifax	Lake Tahoe	Glasgow	Sendai	Sydney	Stockholm Helsinki	Cape Town	Santiago Chile

* Slag conference held in this country or area ° Based upon preliminary programme.

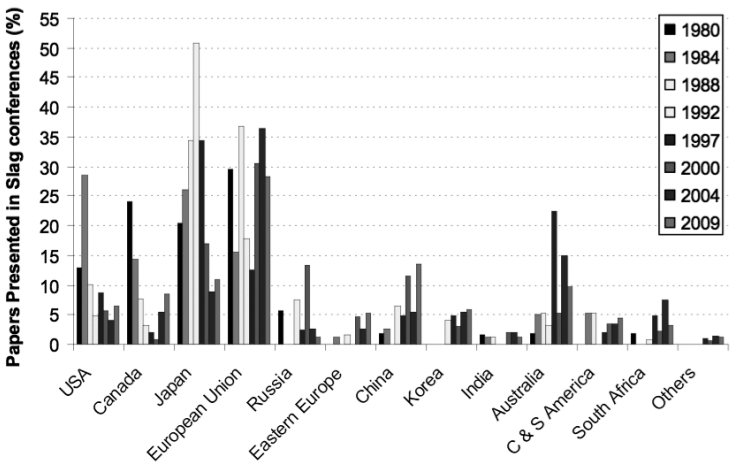

Figure 5: Geographical distribution of papers presented at the slags and fluxes conference series in the period 1980-2008

CONCLUSIONS

From our recent literature review based on METADEX data covering the period 2004-2008, complemented with our earlier reviews from 1979-2003, we can conclude that:

- The publication rate of slag-related research papers showed a peak in 1986 followed by a downturn to a minimum in 1996; after that year the publication rate continuously increased
- The fraction of publications on ironmaking slags has increased to about 25% and is comparable in number of studies on steelmaking slags
- The publications from Japan have remained stable in recent years with a dip in 2003.
- European Union publication rate has increased parallel to the entrance of new member states
- There has been a tremendous increase in the slag-related publications from China, parallel to the ultra-fast growth of iron and steel production in China
- There has been an apparent, marked decrease in the publications of slag-related papers from Russia from 2004 to 2007. If this decrease is genuine, it is difficult to account for
- There has been a dramatic increase in Recycling-and Environmentally-oriented publications in the last few years.

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