Evolution of published research on molten slags and fluxes in the second millennium

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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 carried out for every conference on slags and fluxes. Trends from 1980, the year of the first conference in Halifax, Canada, have been traced and discussed. For the ninth conference in the series, the survey is focused on research on molten slags and fluxes published from 2000 to 2010. In these ten years the centre of gravity of the metals industry has shifted eastwards towards China, and the slags and fluxes literature follows this geographical shift with reference to numbers of papers published per annum. The increased attention on sustainable metals production (including recycling of valuable metals and reuse of slags as cement or construction material) is reflected in the type of research on slags. Minimization of slag production per unit of metal produced is another trend triggering innovative production process development. An in-depth analysis is given of papers published in 2010 in selected journals from China, Europe and USA in terms of slag systems, type of research and geographical origin.

Key words: Literature survey, geography, slag types, slag origin, China

1. Introduction

On the occasion of the 5th International Conference on Molten Slags, Fluxes and Salts in Sydney, Australia, January 1997 organised by Geoff Belton, we made a survey on slag-research for the first time [1]. As a starting point for our survey we selected 1980, the year in which the International Symposium on Metallurgical Slags was first held in Halifax (Nova Scotia), Canada, in August. Charles Masson was the initiator together with Jim Toguri. The unexpectedly large success of this first slag symposium led to a series of International Conferences on Molten Slags and Fluxes, organized every four years in different parts of the world. The Second International Symposium on Metallurgical Slags and Fluxes was organized in Lake Tahoe (Nevada), USA, in November 1984, by David Gaskell. In June 1988 Harry Bell brought the Third International Conference on Molten Slags and Fluxes to the University of Strathclyde, Glasgow, Scotland. The 4th International Conference on Molten Slags and Fluxes was held in Sendai, Japan, under the chairmanship of Shiro Ban-ya.

The overview of slag research became a fixed point in conferences following the Sydney meeting: the 5th International Conference on Molten Slags and Fluxes in June 2000 held successively in Stockholm and Helsinki,

organised by Seshadri Seetharaman and Lauri Holappa [2,3]; the VII International Conference on Molten Slags, Fluxes and Salts in Cape Town, South Africa in January 2004, organised by Chris Pistorius and Kobus Geldenhuis [4,5]; and the VIII Conference on Molten Slags, Fluxes and Glasses MOLTEN2009, in January 2009, Santiago, Chile, chaired by Mario Sanchez [6,7].

In this paper we applied the technology used to detect the trend in research on slags for a limited time period, starting in the year 2000 and ending in 2011 rather than extending the earlier published survey data starting in 1980. We are convinced that the period is long enough to reveal relevant trends. We also did a more detailed survey of leading metallurgical journals. We also analysed in a similar way the preliminary programme of the Ninth International Conference on Molten Slags, Fluxes and Salts MOLTEN12, scheduled for May 2012 in Beijing, China, and organised by Kuo Chih Chou.

2. Methodology

2.1 Data base

A literature survey was executed based upon the METADEX reference source for metals using the key words “slag”, “mould flux”, “casting powder” and “matte” as descriptors. Although the conferences referred to in the introduction also have “salts” in the title we did not use this key word to be able to compare the results of the actual study with the preceding surveys. The abstracts of the papers collected as a result of the query were then individually studied to identify the nature of the research investigation, the type of slags studied and the geographical origin of the research groups and authors involved. In Table 1 the total number of abstracts resulting from the METADEX search is collected and presented by year starting from 1980 up to 2011.

Table 1 Annual number of slag related papers from the METADEX reference source 1980 to 2011

Year	Number	Year	Number	Year	Number	Year	Number
1980	382	1988	459	1996	330	2004	661
1981	378	1989	452	1997	363	2005	648
1982	403	1990	355	1998	375	2006	765
1983	410	1991	367	1999	412	2007	660
1984	427	1992	413	2000	483	2008	854
1985	432	1993	404	2001	461	2009	694
1986	460	1994	370	2002	475	2010	451
1987	432	1995	352	2003	575	2011	186

In Figure 1 the number of published papers per year is shown. The number of publications on slag research as collected from the METADEX data base had a maximum in 2006 with 1021 publications, and then decreased in 2007 to 891, to 854 in 2008 and 624 in 2009. The latter still corresponds to an average of 12 papers published per week. In 2010 the decreasing trend was found to continue: a total of 451 papers were published. Is this a signal that slags as a research topic is losing its attraction for researchers or is this lower value simply an indication that the unknown territory of slags

and fluxes is diminishing? METADEX contained 186 references that fitted our selection criteria for slags on 30th January 2012. From earlier experience we expect another 100 references published in 2011 to be added to METADEX in the year 2012 and 2013. Even with eventually some 290 entrees on slags in 2011 the decrease in slag-related publications is dramatic when compared to the period 2008-2010. The level is also much lower than the average number of slag-related publications in the period 1980-2000.

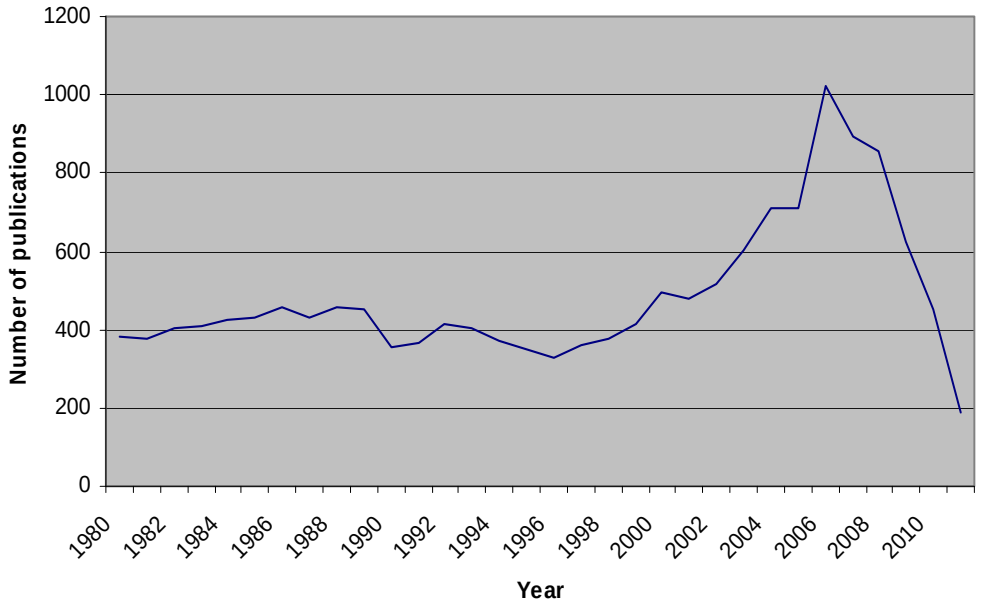

Figure 1 Number of slag-related publications from METADEX data base searches. Early data from [1-7].

2.2 Geographical origin

To relate the slag publications to the origin of the authors the world is divided into United States of America (USA), Canada, Japan, European Union, Russia, Eastern Europe, China, Korea, India, Australia, Central & South America, South Africa and Others. The percentage of papers per geographical area is collected in Table 2 and presented in Figure 2 for the period 2000-2010. For an overview of the period 1979-2000 we refer to our earlier work [1-4].

The results of the 2010 slag research data are very clear: China has continued to lead the production of slag-related papers and is now the origin of 56 % of the slag papers in the METADEX data base. The runner up is the European Union which published 13 % of the collected slag papers, less than a quarter of the Chinese output. Japan is number 3 with 9 % which is lower than the historical annual Japanese average of 11 %. One has to take into account that these comparisons are percentages and that the total world wide production of slag papers has been reduced drastically.

The BRIC countries (Brazil, Russia, India and China) are considered to represent the fast growing economies of the modern world, also in terms of metallurgical industrial activities. There are tremendous differences in slag research in these countries. There is little slag activity published in Brazil. Slag-related publications in Russia, the absolute leader in slag research in the period 2000 – 2005, has almost stopped. The rate of slag –publications in India peaked in 2003 but subsequently dropped. The number of slag publications from India is low when compared with the number of metallurgical faculties and institutes in that fast growing country. China is the only BRIC country that shows a very fast growth in published slag research.

Table 2 Geographical origin of research on slags (%), data for 2000-2008 from [4-7]

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2010
USA	8.1	7.0	8.7	2.1	9.5	6.4	5.1	6.4	2.6	2.7
Canada	5.1	4.4	3.9	4.3	4.1	4.7	3.3	1.7	1.6	1.1
Japan	11.2	14.0	13.1	6.4	14.0	11.0	10.6	10.2	13.4	9.0
European Union	7.4	11.4	9.0	12.8	16.2	14.9	18.8	18.0	13.7	13.2
Russia	28.9	24.9	24.9	40.4	24.0	7.2	3.5	2.3	2.3	0.2
Eastern Europe	4.7	5.8	6.4	2.1	2.8	2.2	2.7	3.1	1.6	0.9
China	19.0	17.1	11.8	8.5	10.3	28.6	36.8	41.3	37.3	56.1
Korea	3.8	3.6	6.9	4.3	2.8	1.7	2.5	2.7	2.6	3.6
India	1.8	2.2	1.5	8.5	4.1	5.3	2.3	4.2	2.6	2.2
Australia	4.0	3.9	4.9	4.3	3.2	3.3	2.8	3.1	2.6	2.9
Central &South America	2.9	4.3	4.1	4.3	6.1	11.7	6.5	2.3	14.7	2.9
South Africa	1.6	0.5	2.6	0.0	0.7	0.6	1.4	0.6	0.7	0.9
Others	1.6	1.0	2.1	2.1	2.2	2.4	3.7	4.1	4.3	4.3

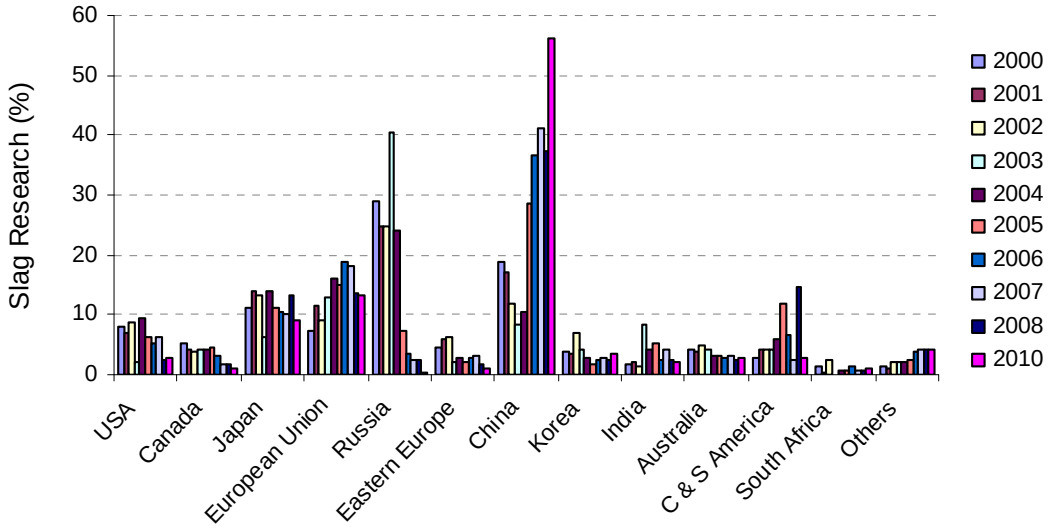

Figure 2 Geographical origin of research on slags (%); data for 2000-2008 from [4-7]

2.3 Nature of research activities

To describe the nature of the research activities on slags, fluxes and mattes the following distinction is made: 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 2000-2008 from [4-7]

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2010
Phase equilibrium/mineralogical	4.6	4.1	4.5	2.3	7.3	2.0	4.4	3.4	2.3	5.1
Thermodynamics	8.4	6.9	7.5	2.3	7.1	8.2	4.2	4.0	5.0	5.1
Kinetics	7.9	3.7	4.3	4.5	5.6	3.3	2.3	2.7	2.0	1.1
Physical properties	11.5	9.7	9.0	2.3	5.9	7.0	5.8	6.5	5.6	6.0
Slag/metal equilibrium	8.4	8.3	12.3	20.5	10.1	8.8	9.6	7.6	6.0	5.5
Plant data/process modelling	38.6	44.1	37.6	34.1	39.5	39.0	38.0	37.4	36.4	31.8
Refractory erosion	1.8	3.0	3.3	2.3	4.4	8.9	12.6	13.4	11.3	11.1
Foaming/smelting reduction	4.9	3.7	3.3	2.3	1.9	1.2	1.1	1.5	1.7	0.2
Modified oxygen steelmaking	0.4	0.2	0.3	0.0	0.7	0	0.3	1.0	0	0.2
Slag splashing	2.9	1.6	1.5	2.3	1.0	1.9	0.8	0.8	0	0.4
Recycling/environmental	10.4	14.7	16.5	27.3	16.5	19.7	20.9	21.7	29.7	33.5

From the statistics it can be concluded that the distribution of different research activities in the field of slags is rather constant with the exception of research on slags focused on recycling or environmental aspects. For the first time this category shows the maximum number of publications, about a third of the total. In an earlier review [6] we noticed that much work is done on re-use of slags and fly ash (coal slag) especially in cement production. One new use of slags is the utilisation of granulated blast furnace (Ironmaking) slags in filters to absorb arsenic from fresh water, thus solving a deadly drinking water problem in certain areas of India [8]. Another original idea is to use steelmaking slags to feed phosphorus to the oceans as there is a shortage in phosphate expected in the near future, which might lead to less fertilizer use in agriculture and eventually to food shortage on a large scale. In the Netherlands a novel method has been developed to produce ferrovanadium from a combination of petroleum fly ash (from power plants) and BOF flue dust (from steelmaking plants) [9].

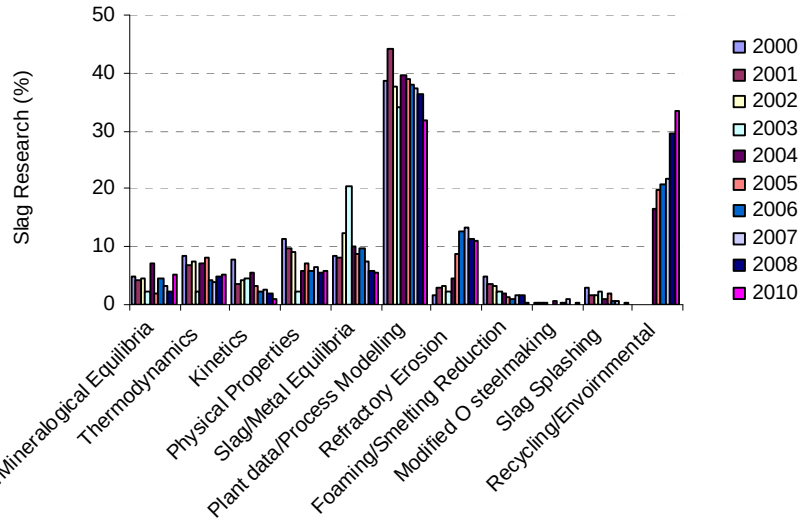

Figure 3 Research activities of slags (%) investigated in the period 2000 -2008; data for 2000-2008 from [4-7]

A large portion of published works is devoted to plant data and/or process modelling but the relative position is decreasing. Nevertheless this type of research is of utmost importance for the improvement of the industrial metallurgical processes in terms of resource and energy efficiency and lowering of waste production. The decrease in number of slag/metal equilibria studies, noted previously, has changed and increased in 2010. Measurements of physical properties maintained a constant level of about 6 %, although such measurements are difficult to execute for molten slags because of the high temperatures involved and the aggressive nature of slags creating container problems.

For a next study the items slag foaming/melting reduction and modified oxygen steelmaking (in fact hot metal treatment in the oxygen steelmaking converter) can be taken out since hardly any slag related work on these topics is being published.

2.4 Types of slags studied

The results of the METADEX analysis in terms of types of slags studied are presented in Table 4 and Figure 4. The types are distinguished according to the process involved i.e. ironmaking, steelmaking, ladle refining, non-ferrous and ferro alloys production, and in mould and weld fluxes, mattes and synthetic slags. Wastes (often referred to as secondary materials) and coal are separate categories.

Iron as master of metals is also mastering the slag research, as in 2010 with the total percentage of publications on iron- and steelmaking and ladle refining slags amounting to 58 %. This is a continuation of the historical trend. The steady increase in non-ferrous slag studies is welcomed as there is still a lot to gain from the efficient processing of non-ferrous metals.

Table 4 Type of slags and fluxes investigated (%), data for 2000-2008 from [4-7]

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2010
Ironmaking	12.6	12.2	11.1	15.9	7.1	23.8	20.3	23.9	23.9	25.4
Steelmaking	20.3	22.0	28.1	22.7	30.7	23.7	18.3	23.8	26.0	18.2
Ladle/refining	7.7	13.6	10.1	6.8	14.1	12.6	19.6	15.5	13.9	14.3
Mould fluxes	7.0	6.8	3.7	0.0	2.9	7.2	5.2	5.6	3.9	5.5
Welding fluxes	1.3	0.9	0.5	2.3	1.2	1.1	3.3	3.7	2.4	1.0
Non-ferrous	15.4	13.1	18.5	36.4	2.9	12.1	10.6	7.1	8.8	10.1
Mattes	10.1	9.8	7.9	4.5	15.3	3.5	6.3	1.5	2.7	0.8
Synthetic	18.7	14.5	11.1	6.8	17.9	9.0	7.5	7.5	6.1	7.8
Ferro alloys	3.3	1.4	3.0	4.5	4.7	2.3	2.5	0.2	2.7	3.4
Wastes	3.5	5.6	6.2	0.0	2.0	1.7	2.4	3.9	3.0	2.5
Coal	-	-	-	-	1.2	3.0	4.0	7.3	6.6	11.1

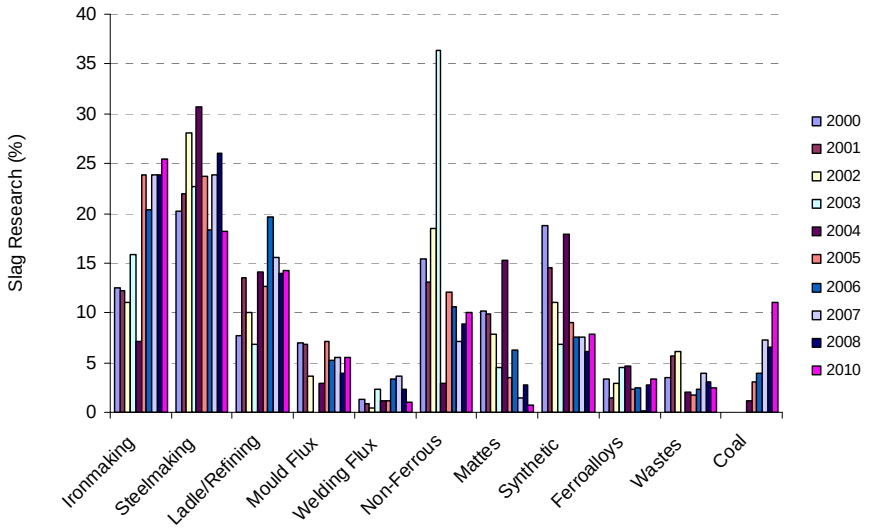

Figure 4 Type of slags studied in the period 2000 – 2010 (%); data for 2000–2008 from [4–7]

2.5 Selected metallurgical journals

To have a more detailed insight in the trends in slag research we selected leading international, metallurgical journals. From North America we chose Metallurgical Transactions, from Europe, Steel Research International, from Japan, ISIJ International. From China we selected two journals published both in Chinese and English, 北京科技大学学报 (International Journal of Minerals, Metallurgy and Materials) and 钢铁研究学报 (Journal of Iron & Steel Research). The content of the International Journal of Minerals, Metallurgy and Materials differs completely from the Chinese version 北京科技大学学报 whereas 钢铁研究学报 is one-to-one translated in English as the Journal of Iron and Steel Research.

Table 5 Distribution of slag related research activities (%) published in selected journals in 2008-2011

	Metallurgical Transactions	Steel research international	ISIJ International	北京科技大学学报 IJMMM
Phase equilibrium/mineralogical	21.8	5.4	24.6	16.7
Thermodynamics	10.3	2.7	11.9	3.3
Kinetics	16.7	9.4	8.5	8.9
Physical properties	16.0	25.5	24.6	24.4
Slag/metal equilibrium	7.7	6.7	17.8	15.5
Plant data/process modelling	21.2	46.3	2.5	12.2
Refractory erosion	0.3	5.4	0.8	1.1
Foaming/smelting reduction	0.1	0	0.8	2.2
Slag splashing	0	0	0	1.1
Recycling/environmental	0.3	8.1	8.5	14.4
Average Slag papers/year (%)	33.3	11.8	10.6	4.3
Total papers on slag	156	63	118	90

Slag-related papers form about 4 % of the papers published in the selected Chinese metallurgical journals whereas the other journals devote 11 to 33 % of the papers to slags and fluxes (Table 5). Most work, from 16 % to 26 %, is focused on the determination of physical properties of slags: this figure is significantly higher than that derived from the METADEX survey which covers all relevant journals. Phase equilibrium, slag/metal equilibrium and thermodynamics added together represent 35 % of the slag-related papers. Recycling and environmental aspects of slags are described in 14 % of the papers, indicating the importance of these aspects. Some 12 % of the papers deal with plant data and process modelling. Kinetic studies are published in about 9 % of the papers. Although slag splashing is applied in most steelmaking plants in China [10] to increase the lining life of the converters (from 700 heats to 10 000 heats) only 1 publication was devoted to this technology. Foaming and smelting reduction form a minor part of publications on slags.

Table 6 Type of slags and fluxes investigated (%) published in selected journals in 2008-2011

	Metallurgical Transactions	Steel research international	ISIJ International	北京科技大学学报 IJMMM
Ironmaking	6.4	22.1	28.8	12.2
Steelmaking	10.5	33.8	26.4	14.4
Ladle/refining	6.4	22.1	6.8	21.1
Mould fluxes	5.8	18.2	16.1	17.8
Welding fluxes	0.1	1.3	0.8	0
Non-ferrous	22.8	0.0	1.7	3.3
Synthetic	38.6	2.6	14.4	6.7
Ferro alloys	7.0	0.0	4.2	3.3
Wastes	1.8	0.0	0.8	21.1

Table 7 Geographical origin of research on slags (%) published in selected journals in 2008-2011

	Metallurgical Transactions	Steel research international	ISIJ International
USA	11.1	2.6	3.6
Canada	9.1	2.6	2.2
Japan	3.3	13.2	47.5
European Union	21.6	43.4	5.8
Russia	0.7	0.0	-
Eastern Europe	2.0	1.3	-
China	9.8	19.7	10.2
Korea	9.8	6.6	15.4
India	ID	1.3	2.2
Australia	21.6	3.9	8.0
Central/South America	3.9	2.6	2.2
South Africa	0	0.0	-
Others	8.5	2.6	2.9

The slags investigated by Chinese authors (Table 6) are for 21 % waste slags, stressing the care for safe deposit of waste slags or secondary use of these types of slags. This is comparable to the relative interest in ladle and refining slags. Ironmaking and steelmaking slags cover a quarter of the slags investigated. Mould fluxes are also frequently investigated, which makes sense in a country where newly constructed plants are 100 % based on continuous casting. Non-ferrous and ferro-alloy slags are topics for study but are at a low frequency. There is no research on welding fluxes published in the Chinese journals in the period 2008-2011 in contrast to the other selected journals.

In Table 7 the geographical origin of the research on slags published in selected non-Chinese journals is presented. Almost all papers in selected Chinese journals are written by Chinese authors. In Metallurgical Transactions an equal share (20-22 %) of slag-related papers is published from USA/Canada, the European Union and Australia. China and Korea deliver each about 10 % of the papers. In Steel research international the majority of slag-related papers (43 %) origins from the European Union, followed by China (20 %) and Japan (13 %). In ISIJ International almost half (48 %) of the slag-related papers is work from Japanese authors. Korea (15 %) and China (10 %) follow as second and third.

2.6 Conferences

The Molten 12 Conference is organised in Beijing, China, and as is clear from Table 8, this is a home game for the organising country. Out of a total of 51 papers, 48 (94 %) are written by researchers from universities or specialised research institutes with a large share for USTB. Only 3 papers, representing 6 %, are contributions from big steel companies, Anshan and Baoshan. This is typical for the trend in the Molten Slags and Fluxes conferences: most work is done at universities on laboratory scale experiments and by means of powerful computers for modelling. Still there is need for data collection from real industrial scale processes, for which the contribution of leading metallurgical companies is absolutely necessary.

Table 8 Geographical origin of papers published in Conference Proceedings or Programmes (%), data for 1979-2012

	1980	1984	1988	1992	1997	2000	2004	2009	2012
USA	13.0	*28.6	10.1	4.8	8.6	5.6	4.1	6.5	5.4
Canada	*24.0	14.3	7.6	3.2	2.0	0.9	5.4	8.4	4.1
Japan	20.4	26.0	34.4	*50.8	34.3	16.9	8.8	11.0	7.7
European Union	29.6	15.6	*36.9	17.7	12.5	*30.5	36.4	28.3	29.4
Russia	5.6	0.0	0.0	7.4	2.5	13.4	2.7	1.3	2.7
Eastern Europe	0.0	1.3	0.0	1.6	0.0	4.6	2.7	5.2	5.0
China	1.9	2.6	0.0	6.5	4.9	11.6	5.4	13.5	*22.6
Korea	0.0	0.0	0.0	4.0	4.9	3.0	5.4	5.8	6.3
India	1.7	1.3	1.3	0.0	0.0	2.0	2.0	1.3	0.0
Australia	1.9	5.1	5.2	3.2	*22.5	5.2	14.9	9.7	10.4
Central &South America	0.0	5.2	5.2	0.0	2.0	3.5	3.4	*4.5	1.4
South Africa	1.9	0.0	0.0	0.8	4.9	2.2	*7.4	3.2	1.8
Others	0.0	0.0	0.0	0.0	1.0	0.7	1.4	1.3	3.2
Place slag conference	Halifax	Lake Tahoe	Glasgow	Sendai	Sydney	Stockholm Helsinki	Cape Town	Santiago	Beijing°

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

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