1. Introduction

1968 I visited Japan for the first time: Kyoto–Foundry Conference, heard many lectures and saw several foundries and steel works—this was not new for me—but Japan and the Japanese were so different: kind and helpful and the culture with shrines and temples and the living style with “tatamis” and “kotatsu” were astonishing. I wanted to come back to this country as soon as possible, see Figs. 1 and 2.

But at first I had to finish my “Habilitation”—senior lecturer; two lecture series I had already prepared and printed in Germany for Nippon Kokan and Tokodai: “direct reduction with coal-gasification and atomic heat” and “agglomeration of iron ores”; see Figs. 3 and 4.

Furthermore I gave many lectures in 1973 at several universities from Hokkaido to Kyushu and visited many companies to discuss e.g. about blast-furnace-problems.

The most important result: I got many friends and this did not change in the coming years!

Back in Germany I brought with me many questions e.g. why is my Aachen-University in Aachen?

In 1865 one of the best equipped steel-works with Thomas-Converter was built up in Aachen “Rothe Erde”, sometimes more than 5,000 workers were earning their income there. It started by a new situation: no steel should be imported to Germany, but clever merchants found out that the import of cheap pig iron was allowed! Therefore pig iron was transported from many countries: Belgium, England and Luxembourg just behind the border to Aachen and was changed into steel. That means in Aachen steel-works there was never a blast furnace, no coke-oven and no sinter-strand. See Figs. 5 and 6.

This changed in 1926 when the company made bankruptcy and also shop owners and coworkers of small companies

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**Fig. 1.** 35th Foundry Conference in Kyoto.

**Fig. 2.** Plant-Visit.

**Fig. 3.** Discussions at Nippon Kokan.

**Fig. 4.** Discussions at Tokodai (Tokyo Inst. of Tech.).
became unemployed.

In the prosperous time our University was founded. After chemistry, mining and electro-technics our institute of metallurgy started in 1910. The next shock came with the second world war, see Figs. 7 and 8.

Today our Institute looks like this and our laboratories were build on the other side of the street, see Figs. 9 and 10.

Our Department of Ferrous Metallurgy is divided into two sections, see Fig. 11; Figs. 12 to 14 show pictures of the process metallurgy group in the last years.

2. Research and Development

In the department of Metallurgy at the RWTH-Aachen already in 1982 the source and decrease of CO₂, the greenhouse-effect and the influence of the steel industry was investigated. The possibility to bring the CO₂ as dry-CO₂-ice blocks in the deep sea seemed to be an interesting way. Industrial produced CO₂-ice has a density of \(1.4\to 1.6\times10^3\) kg/m³ and is heavier than water. In tests the sublimation of CO₂-ice in salt-water was measured and concluded that CO₂-ice-blocks would get a small shell of water-ice but the sublimation of CO₂ will be very slow.¹

In a project a combined steam-CO₂-injection to foam
was discussed to increase the flooding efficiency of tertiary crude oil production; this foam was used to increase the oil-production. By pressing out sticky oil with hot water often happened an “overriding” of the watersteam and the oil remained in the earth. By foam this overriding was blocked and the oil could be pressed out; CO₂ was a suitable gas for the foam formation and also made the oil less sticky,²–⁴, see Fig. 15.

Parallel to these research activities special subjects in the field of metallurgy of iron and steel were investigated. Aichinger gave in 1991 the development of the specific CO₂-emission of the steel industry.⁵ Ameling showed that to bring down the CO₂-output by different ways was more interesting in the following years than the use of CO₂ see Fig. 16.⁶

To produce a reduction gas by gasification of coal, biomass or waste with air, oxygen and watersteam the influence of CO₂ was studied in the High Temperature-Fluidized-Bed-Reactor, see Figs. 17 and 18.²–¹⁰

Also in the field of Underground-Coal-Gasification CO₂ was used including high pressure in research projects; on the one hand the reactions of gasification were influenced on the other side a lot of CO₂ was thought to remain underground, see Figs. 19 and 20.¹⁷–¹⁶

In the field of Direct- and Smelting reduction research activities were carried out in rotary kilns to explain swelling, sticking, plating and scaffold formation.¹⁷–²⁰ Beside reduction and smelting e.g. in shaft furnaces the reduction behavior was studied in fluidized beds including treatment of wastes and with different gases.²²–²³
The step from hematite to magnetite may already show cracks and disintegration, wustite shows a loss in strength and the increase in porosity and the iron precipitation by needles may cause swelling with an extreme volume increase and also sticking, see Fig. 21.

By research in a REM with the facilities to work with high temperatures and reduction gases it was possible to show that the needles are growing from the bottom and not from the top, see Figs. 22 and 23.

Under reduction atmosphere—mainly by hydrogen it is possible to get planar and dense iron precipitation, see Fig. 24. Under special conditions also plating may occur; therefore this effect will be researched intensively with different ores.27)

Figure 25 shows that by increasing reduction and increasing temperature at the surface of a pellet an iron shell was formed with molten FeO-containing material inside and this was dropping down.28)
The behavior of briquettes with embedded carbon and self-reducing pellets was investigated. Tests with briquettes dust from iron and steel industry were performed. The briquetting process and the reduction behavior of briquettes produced from different dusts, bound by different binders and with different carbon contents were studied. Due to the fast reduction of the iron oxides at the outer part of the dust briquettes a iron shell was formed.

The increase of temperature to simulate the moving down in a shaft showed that the half-reduced material in the middle part of the briquette can be smelted. Further increase of temperature causes collapse of that shell. Finally a completely separated slag and metal phase occurred, Fig. 26. Based on the experience in laboratory tests industrials tests in the Hamborner Shaft Furnace “Oxicup” has been successfully done with briquettes.

It is well known that the reduction of pellets and briquettes is associated with a volume change. Swelling of agglomerates has two major drawbacks: loss of strength and disintegration, which gives rise to operational problems in reduction furnaces. On the other hand, shrinkage of agglomerates may be profitable for reduction processes because it may increase the strength of pellets and briquettes during the reduction.

Beside the behavior of briquettes pellets with embedded carbon were studied. In these campaign only shrinking was observed, see Fig. 27.

To discuss these results in detail further reduction tests were carried out with different ores and different carbon containing materials e.g. coals, char and plastics, see Figs. 28 and 29.

Interesting is one of these results, that some pellets show some initial swelling but furtheron only shrinking. By addition special mixture of reduction agents the shrinking behavior can be controlled.

This research will be continued to discuss the different reactions of reduction and smelting of big-, small briquettes and pellets.

In the following subjects are stressed about fines and CO₂-injection into Electric Arc Furnace (EAF). Beside different theses on EAF e.g. by FTIR (Fourier Transform Infrared Spectroscopy) the waste gas of an EAF was measured continuously online. Wiryomijoyo showed in his thesis that the CO₂-emission from steelmaking depends on the use of energy sources and reduction agents; the discussion of CO₂-emission as a global problem lead the world steel industry into this important subject. The problems of waste and rest fines materials should be considered, too. The initial observation were done by thermodynamic calculations as well as ChemSage simulation.

Fig. 25. Hollow icicles.

Fig. 26. Reduction and smelting mechanism of briquettes with embedded carbon.

Fig. 27. Shrinking of pellets with embedded carbon.

Fig. 28. Effect of temperature and anthracite content on the volume change.

Fig. 29. Weightloss of CVRD-Pellets with 8% DSD and 10% anthracite.
and literature research conclusions. By experimental tests in the steelworks at Krakatau-Steel in Indonesia and in Department of Ferrous Metallurgy RWTH Aachen it was concluded that the overall performance of electric arc furnace can be increased by injection of CO$_2$ and fines material. In some of the direct reduction processes like HyL-III, Finmet and Iron Carbide CO$_2$ will be blown continuously from its separation of the reduction gas cycle.

On the other side the steel industry is facing a problem of fines generation and its handling. The industrial as well as laboratory experiments were conducted to analyze the influence on metallurgy as well as energy saving by CO$_2$ and fines injection. The industrial experiments conducted in the steel works of PT Krakatau Steel (PTKS), Indonesia, were divided two parts of experimental stages. In the first stage, CO$_2$ and DRI fines were injected into a 2 t EAF. The results showed that due to the injection of CO$_2$ and fines, the built up of foaming slag were accelerated. The melting energy was influenced by the generation of CO gas as well as slag foaming. After the reviewed first stage results, the second stage experiment were arranged in the 120 t EAF of Slab Steel Plant PTKS, see Fig. 30. In this case, around 22 000 Nm$^3$/h CO$_2$ were blown from HyL-III direct reduction plant from the separation continuously in the reduction gas circuit. The fines DRI are produced approx. 450 t/d from both HyL-I and HyL-III direct reduction plant.

In this project, the injection of fines DRI as additional charge material for EAF was initiated. The results brought furthermore the advantages of the gas injection as stirring energy for a better metallurgical process in EAF. The laboratory experiments were introduced to explore details of the results of the industrial experiments. A laboratory scale of EAF was developed and constructed in Department of Ferrous Metallurgy, RWTH Aachen. The furnace was constructed with a furnace vessel and a roof; it was equipped with a 9.7 kVA DC source, an electronic control of the graphite electrode, injection equipment, computerized process data acquisition and online temperature measurement. The melt capacity is approx. 5 kg. see Fig. 31.

The generated CO was also observed in the industrial experiments and was directly burned as part of the post combustion process in EAF. The influence of the different injected gases like argon, air and CO$_2$ was measured. By CO$_2$-injection a decarburization takes place and the CO-

amount increases together with a slag foaming. Adding of carbon can stop the decarburization and the Fe-fines injection increases the steel amount. These experiments with foaming slags, e.g. by adding different coals will go on.\[44\]

The High-Turbulence-Mixer (HTM) was developed to stir molten metals without injection of gases but by induction forces. Improved product quality can be achieved by the application of a number of metallurgical treatments at different stages in the iron-and steel-making route, each one tailored to match local conditions and taking best advantage of them. In this respect, the mixing of active substances such as slag, powders and gases with liquid metal is a very important and decisive step for desulphurization, deoxidation, degassing, as well as alloying and inclusion control. Furthermore dusts and wastes can be treated without any gas injection.\[45,46\]

The HTM enables easier mixing of different materials with molten metals involving minimum material loss. It is especially suitable for the mixing of granulated materials and substances in powder form. Due to its mixing ability, the HTM technology will speed up the processing rate by using it either batch-wise in small reactors or continuously. The HTM-reactor is a cylindrical lined vessel filled with liquid metal. The metal is stirred by inductive forces caused by the electromagnetic stirrer beside (see Fig. 32.). Two waves are moving to the top of the vessel until they hit together and so a kind of vortex is created. The small batch-wise working reactor is able to treat one ton of liquid metal and is presently used in different foundries.

In order to avoid heating losses of the melt the second continuous working version of the HTM was built in connection with an induction furnace to treat around 4.5 t of liquid metal. Research tests under different mixing conditions are also done in this reactor on such material as shred-
**der-light-fraction and pyrolytic coke,** dusts, sponge iron and additions. In the HTM-reactor hot metal has been desulphurized intensively by addition of lime. The process was also used successfully to produce nodular iron by addition of Mg with small losses by burning. The behavior of Zn out of EAF-dust in the HTM is presented and discussed. Lead was treated in the same way with similar results.

In contrast to the behavior of zinc and lead which are evaporated, chromium and nickel coming from stainless steel dust are enriched in the iron bath. The produced slag does not cause problems when leaching tests are performed.

In special cases chromium and nickel can be defined as impurities; these elements can be removed separately by oxidation with iron ore and pure oxygen or diluted by addition of DRI. Beside metallurgical tests research was done to improve the refractories and energy consumption.

Investigations of solid injection and bath stirring using a coherent jet are made, to get a fast, efficient and costsaving addition of alloys, fluxes and recycling material. Figure 34 shows a setup of a coherent-jet-injection-test, where the core jet is protected and kept together by a flame-shroud jet. The solids are injected deep in the melt together with the core jet—Figure 35 in a water model.

Figure 36 shows a hot injection test at the department and Figure 37 documents the effect of carbon injection.

In addition to injection of solids in melts injection trials in shaft furnaces were made, e.g. to bring in foundry dusts in cupola-furnaces. This was possible in large-scale with different materials, e.g. like plastics. The result showed that no dioxins appeared in the off gas.

Beside injection into an imperial smelter research was carried out to recycle foundry dusts into cupola-furnace. The different circumstances in the tuyère level had to be studied and discussed.

To increase the injection rate of unburning material a new process was developed. Parallel to test at a cupola furnace an injection-coke-bed-simulator was built up at the institute, see Figures 38 and 39. In this aggregate dusts are injected by a natural gas/oxygen-burner. Aim of this research is to study the behavior of such hot gas injection with dusts on the coke and in the furnace.

By blast-furnace research within the last decades the productivity has steadily increased. Test were done to understand e.g. the cohesive zone in hot tests, see Figure 40, in cold tests, see Figure 41, or by electric sensitive paper, see Figure 42; naturally a lot of computer simulation followed.
To predict the reactions in the blast furnace more detail knowledge and real online results were needed e.g. the depth of the raceway with and without injection \(^{60}\) (see Fig. 43) and the change of the geometry of the raceway in a running thesis. \(^{61}\)

Together with ThyssenKrupp also results about the gas composition in the raceway were studied by laser and discussed\(^{62}\). In another European program in labs at Aachen and at industry with ThyssenKrupp, Rautaruuki and Aceralia the top gases of blast furnaces were measured stressing the online data especially of zinc and alkalies see Fig. 44 \(^{63}\). Parallel to these tests online tests about the temperature and composition of metal melts by LIBS were done. \(^{64,65}\) Figure 45 shows the shematical system and Fig. 46 the running equipment. With this method it is possible to measure online the concentration of process relevant ele-
In these days tests are running in an European research program in Aachen and in Spain to measure online with an adapted equipment steel slags. The Department of Ferrous Metallurgy a laboratory rig was developed to investigate pulverized coal injection in detail. This rig simulates the behavior of fines injected into the raceway of the blast furnace. The coal sample is blown by a shock wave into preheated gas with 1 100°C, simulating the hot blast, mixed with it and passed through a high temperature zone of 1 700°C, simulating the raceway. The conversion gases are analyzed to their contents of CO, CO₂, CH₄, H₂ and O₂ and the conversion degree is calculated.

While simulating blast furnace conditions the effect on the ignition and conversion behavior of different coals such as porosity, particle size, content of volatile matter, carbon and ash or injection rate could be tested. Further investigations were performed to analyze the effect of catalysts on coal conversion, oxygen enrichment of the hot blast, preheating of the injected coals or different lance geometries. The results obtained have shown that they are transferable to the real blast furnace.

Also tests and discussion started to inject coal mixed with different fine materials. The reasons for a combined injection of coal and fine iron ore or iron containing dust are various, e.g. the amount of fine ore increases steadily due to a decreasing number of high-grade lump ores. The injection of fine iron ore to substitute pellets or sinter and herewith to reduce agglomeration and pig iron costs and energy.

For the different proposes the rig was steadily adjusted, the latest situation is shown Figs. 47 and 48.

The laboratory experiments have shown that a complete reduction of hematite iron ore to metallic iron is possible within the short residence time of 10–20 ms. Therefore further experiments were performed with blast furnace flue dust, steel plant residues and rolling mill scale. Concerning the iron and carbon content of these materials an injection into the blast furnace seems to be possible. Figure 49 shows the results of a combined injection of flue dust and coal.

Further research about the race way brought results and knowledge about different materials, e.g. pet coke, BF-sludge, activated carbon and catalyst mostly as mixture with coals. Figure 50 shows the influence of mixtures of different coals and mixtures of waste with coal.
Beside injection of solid materials the recycling of treated BF-topgas or hot reduction gas produced in gasifier out of carbon, waste materials and biomass is researched. It was found that these gases containing mostly CO and H\textsubscript{2} are suitable to decrease the coke rate, to influence the gas flow and to minimize the CO\textsubscript{2} output.\textsuperscript{81–84) Figures 51 and 52 show the influence of hot reduction gas.

3. Some Forecasts

After a review to the steelworks “Rothe Erde” and our institute of ferrous metallurgy at Aachen some members and results are shown e.g. CO\textsubscript{2}-ice-blocks in the deep sea—today the “Researchship Polarstern” is feeding the ocean with iron that the seaweeds pick up intensively CO\textsubscript{2}.\textsuperscript{85) After mentioning the fluidised-bed-gasification of coal biomass and waste with using CO\textsubscript{2} and underground-coalgasification with CO\textsubscript{2}—today old mines are used for deposit of CO\textsubscript{2}, proofed by the geological institute, Aachen.\textsuperscript{86) By research it was found that CO\textsubscript{2} increases the tertiary oil production—today it is planed to use the CO\textsubscript{2} from H\textsubscript{2}-iron ore reduction for this purpose. The use of H\textsubscript{2} for direct reduction is proofed. The use of CO\textsubscript{2} for slag foaming and better mixing is proofed. Coherent jet technology is increasing the efficiency of solid injection. With the better knowledge of blast furnace behaviour by laser technique in the raceway and also at the top of the furnace and in the molten products it is proposed to use hot reduction gas. Interesting ideas like microwave for steel production\textsuperscript{87) and in the next figures some possibilities are shown, which are mentioned in the ULCOS-project,\textsuperscript{88) see Figs. 53(a) and 53(b).

This will be taught and discussed in German lectures at our Institute at Aachen and also in English language in our master courses\textsuperscript{89) and by distance learning.\textsuperscript{90) REFERENCES

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