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Applying virtual reality model to green ironmaking industry and education: ‘a case study of charcoal mini-blast furnace plant’

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ABSTRACT
A virtual reality (VR) model has been developed in the case of a generic green ironmaking industrial unit, namely a typical charcoal mini-blast furnace (CMBF) plant in Brazil. The VR prototype construction of the CMBF plant has been implemented through integration of data in different softwares and hardwares, including detailed engineering design of various auxiliary units and major equipments with realistic project parameters. Through the VR technology, one can actually have the unique experience visiting all parts of the CMBF plant, promote technical discussions on engineering and process control with users and improve information handling, communication, safety, maintenance procedures and development of advanced engineering projects in the field. VR industry-professional education platform can be used in universities, museums and industries with great benefits to students, workers and users.

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KEYWORDS
Virtual reality; charcoal blast furnace; green ironmaking

Introduction
Since the last decade, virtual reality (VR) technology is being applied in different areas, including mining, metallurgy, aerospace manufacturing etc. (Woksepp et al. 2005; Zhou 2011; Hugues et al. 2012; Vieira et al. 2014; Frigo et al. 2016). VR has also been integrated with the computational fluid dynamics (CFD) models for coke blast furnaces (Zhou 2011). The objective of this work is to highlight plant layout, equipments and processing with a view to integrate, academic and theoretical background of students with actual practices in manufacturing environments such as CBMF. The VR factory contributes significantly to make engineering education practical oriented and for training technical personnel in the actual industrial units.

Green pig iron production in charcoal mini-blast furnace (CMBF) plant
There are many CMBF plants located in different regions of Brazil essentially using charcoal as fuel. Charcoal is manufactured by carbonization of wood derived from eucalyptus trees in special furnaces in the absence of air. There is continuous planting of these trees so that at any point of time, planting and cutting of the trees are in steady state. As such there is no destruction of forests for the production of charcoal in this technology. Pig iron produced in CMBFs is sold to steel industries and foundries in the domestic market and are also exported. The pig iron production through this route amounted to 10,000 kt year\(^{-1}\) in 2004 and 5,400 kt year\(^{-1}\) in 2013. There are approximately 148 CMBF’s, and 67 commercial pig iron manufacturers located in different parts of the country, having a total installed capacity of 14,800 kt year\(^{-1}\) of pig iron in January of 2014. The states of Minas Gerais, Pará and Maranhão are the largest green pig iron producers in Brazil (Paula 2014). In many of these plants, the top gas of the CBMF, after the usual gas cleaning procedures is used for heating of the blast and electrical power generation. Table 1 contains CMBF data and parameters.

Figure 1 presents a typical flow chart of the production chain covering, from planted eucalyptus forests, conversion to lump charcoal using carbonization furnaces to the end product. The usual ore burden charged into the CMBF is composed of haematitic or itabiritic lump ores from the mines.

Many of the CMBF ironmaking plants in Brazil, have modern equipments and operate with least impact on the environment. In the last 15 years many of these plants have started having control systems based on thermochemical and other models and sensors for monitoring the operation of the furnaces and improving...
the efficiency (Castro et al. 2005). In this paper the authors have also discussed the differences between operational parameters of charcoal and conventional coke blast furnaces based on the physicochemical characteristics of the two fuels. Charcoal blast furnaces in general are smaller in terms of height as charcoal has lower compressive strength and higher reactivity relative to coke. There have been publications in the area of mathematical models of charcoal blast furnace based on heat mass and momentum transfer equations (Miwa et al. 1985, 1989; Miwa and Seshadri 1989, 1991). The solution of the resulting differential equations give the variation in the composition profile of reduction of iron ore and gases in the shaft as a function its height. Technological improvements and the recycling measures and green practices with sustainable charcoal production from the plantations of eucalyptus have made this process quite ecofriendly.

### Methodology

The VR integrated system consists of various components such as commercial VR software, immersive drivers, workstation, 3D projector, infrared emitter and 3D shutter glasses, specifically meant for stereoscopic visualization in the VR model of the prototype. The construction of the generic VR plant has been achieved through integration of different softwares and hardwares with detailed engineering design of main equipments and auxiliary units of a typical green charcoal mini-blast furnace (CMBF) ironmaking plant. The detailed engineering project was developed with the support of JB company in Brazil. This contribution to charcoal blast furnace technology is first of its kind and has been a pioneering effort.

The first phase this project utilized 2D CAD (computer-aided design) drawings of basic engineering project of CMBF green iron making unit. In the second phase, all systems and subsystems of the plant 3D models were generated from 2D drawings using a 3D authoring software. Subsequently photo-realistic texture applications were carried out using 3ds Max

### Table 1. CMBF data with typical parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Useful volume in m$^3$</td>
<td>90–350</td>
</tr>
<tr>
<td>Productivity index/t day$^{-1}$ m$^{-3}$</td>
<td>1.8–2.4</td>
</tr>
<tr>
<td>Useful height/m</td>
<td>13–17</td>
</tr>
<tr>
<td>Hearth diameter/m</td>
<td>1.5–6.0</td>
</tr>
<tr>
<td>Hot metal temperature/°C</td>
<td>1380–1480</td>
</tr>
<tr>
<td>Slag rate/kg t$^{-1}$</td>
<td>120–300</td>
</tr>
<tr>
<td>Basicity of slag (%CaO/%SiO$_2$)</td>
<td>0.75–0.95</td>
</tr>
<tr>
<td>Top gas index (%CO/%CO$_2$)</td>
<td>0.9–1.3</td>
</tr>
<tr>
<td>Top gas temperature/°C</td>
<td>80–150</td>
</tr>
<tr>
<td>Top gas dust content after cleaning/mgNm$^{-3}$</td>
<td>&lt;10 or &lt;50 or &lt;100</td>
</tr>
<tr>
<td>Blast temperature/°C</td>
<td>750–800</td>
</tr>
<tr>
<td>Bulk density of charcoal /kg m$^{-3}$</td>
<td>180–240</td>
</tr>
<tr>
<td>Carbon rate/kg t$^{-1}$</td>
<td>420–480</td>
</tr>
<tr>
<td>Fuel injection rate /kg t$^{-1}$</td>
<td>60–120</td>
</tr>
<tr>
<td>Sludge after treatment /kg t$^{-1}$</td>
<td>5–30</td>
</tr>
<tr>
<td>Material from expanding balloon/kg t$^{-1}$</td>
<td>10–50</td>
</tr>
<tr>
<td>Number of tuyeres</td>
<td>13–17</td>
</tr>
</tbody>
</table>

Figure 1. Flowchart of green pig iron production in charcoal mini blast furnace in Brazil.
software in order to give the components of these systems and subsystems an appearance close to reality. The last phase is the conversion of the 3D model to VR model. This was done using a ‘plug in’ of a specific VR software from Siemens. This VR software employed for this purpose is Comos Walkinside (Walkinside Academic Package), which is compatible with the most of CAD formats available in the market.

With the use of ‘avatar’, available in the VR software, one can access to all the local plant premises using the third person view of a human figure. Thus the user is capable of simulating the physical constraints, such as gravity, obstacles, bumps and actual dimensions of the real world into the virtual factory. Various other features available in Comos Walkinside have also been included in this virtual model, such as introduction of 3D sounds for pumps, compressors and alarms. Besides, it is also possible to simulate several critical situations such as smoke fire and gas leaks incidents to enable response training and plant evacuation.

Hyperlinks for illustrative 2D films and presentations relating to operating practices, characteristics of equipment, material and heat balances of process, typical operational parameters, process control model and other technical details have also been incorporated in the VR model. Besides a 360° photo library of illustrative pictures of several CMBF units are made available. All photos were taken using Samsung Gear 360 camera. The preview of the photos can be done using the Samsung Gear VR which is a mobile VR headset developed by Samsung Electronics.

Salient features of different sectors of the VR model

Figure 2 shows a representation of VR engineering project for a generic non-integrated CMBF plant to produce green pig iron. The tour through various sectors of the plant is a unique experience. The VR model can be a base for improving the engineering design of different auxiliary units and process control for increased productivity. The main individual 3D systems of the VR model are described below.

Yard for receiving raw materials

The VR plant has a raw materials yard with an area of 10,000 m² and with a storage capacity for up to 40 days
of production. In this yard, shown in Figure 2, there is provision for storage and handling of manganese ore, quartz, scrap and various types of fluxes, such as dolomite and limestone, as well as different types of haematitic and itabiritic ores.

Receiving, storage and preparation system of charcoal

The virtual receiving system is for two types of trucks used in Brazil to transport charcoal (inside bag or cage). A total capacity of this system is up to 400 m³ h⁻¹ of charcoal. The virtual storage system is represented in Figures 1 and 2. It consists of a central deposit with a storage capacity of 13,000 m³ and an auxiliary bin, located on the top of the main conveyor with a storage capacity of 120 m³. The sized and homogenized lump charcoal inside in this bin is dosed by weight batching to be charged into the furnace. This project is designed to minimize the bulk density variation of the lump charcoal to be charged into the CMBF. The system for charcoal preparation consists of a sieve of two decks with the sieving capacity of 250 m³ h⁻¹ and 2 metering hoppers of 10 m³ each.

Storage and preparation system of raw materials (SRM)

The VR model of SRM, given in Figures 1 and 2, includes a system composed of the yard of raw materials, the auxiliary deposit and the main storage SRM with thermal treatment of lump ores. The 3D model of the main system is composed of 20 cells, and 16 for lump ores and 4 for fluxes, and has capacity to store 2,800 t of lump ores. Within each cell there are many multiple metallic tubes containing holes, which enable hot gases (150–250°C), coming from the glendons to perform the operations of drying and thermal treatment of lump iron ores. The standard residence time of ores for this operation can vary from 24 to 48 h depending on the geological and mineralogical characteristics. This system is able to feed the CMBF at a rate of 50 t h⁻¹ of dry lump ore. This operation has the objective of minimizing the intensity of decrepitation of haematitic and itabiritic lump ores. Industrial results have shown that it is possible to increase up to 15% of the annual output of the CMBF and a reduction of 5–8% in the specific consumption of charcoal.

Main charging system for raw materials and charcoal (MCS)

The 3D model of MCS is composed of a conveyor belt with a width of 1.07 m, a rotating hopper, two fixed hoppers, a set of sealing cone type, a distributor with metallic plates, equalizing valves and automatic and manual probes. The first hopper has a carbon steel cone actuated by a pneumatic cylinder. The second hopper consists of a bowl and a manganese steel cone and actuated by a pneumatic cylinder. Different views of the burden distributor with plates are shown in Figure 3.

Description of charcoal mini-blast furnace 3D model

The 3D furnace model, shown in Figures 1 and 2, is a virtual replica of a CMBF with 15 m useful height, 12 m² of hearth area and a useful volume of 200 m³. It consists of arrangement 14 electrolytic copper tuyeres with continuous refrigeration system, having water circulation with mass flow control to regulate the temperature.

The hot metal tapping area consists of a pneumatic drilling machine to effect opening of the tap hole, a hydraulic mud gun for injection of mass to close the tap hole for buffering the furnace and a spout for tapping of hot metal and slag (Figure 4). The system also contains a ladle to pre-treatment of hot metal. The virtual furnace was designed with one tap hole.

The refractory lining of the furnace is of silico-aluminous type with cooling of the carbon steel shell by water from a spray nozzle. A closed circuit system has been used for this purpose. All the refractory bricks were designed and textured individually in 3D.

Air blast heating system (ABHS)

In most of the CMBF units in Brazil, glendons serve as air heating system. The virtual ABHS model consists of three heat exchangers operating in parallel as shown in Figures 1, 2 and 5. These devices are regenerators for heating the air blast to 780–820°C using 12 tubular stainless steel coils for each glendon. The walls and sills of ABHS are composed of refractory bricks and thermal insulation. The metal roof consists of ceramic fibre modules in the frontal region. For the combustion chamber and other parts of the ceiling, refractory bricks with an insulating layer of concrete has been used.

The gaseous fuel used in the operation of glendons is clean top gas. The air to be heated and blown in the CMBF passes through the inside of the coils and is heated by combustion gases generated in the front chamber of the glendon. One portion of combustion gas is used for drying and heat treatment of lump ores in the main system storage.

Blow house equipment and machinery (BHEM)

The virtual model of BHEM is comprised of a turbo blower as the main equipment as shown in Figure 6. Further, the engine room has five centrifugal blowers, with nominal capacity of 38,000 Nm³ h⁻¹ of air blast and with a blowing pressure varying from 0.9 to
Figure 3. Different views of the burden distributor with metallic plates. 1: A 3D draw showing the furniture of the distributor equipment; 2: A screenshot inside the VR blast furnace model showing the distributor with plates in the top of the reactor; 3: An illustrative 2D draw showing the distributor with plates and the profile of burden distribution on the top of the CMBF; 4: A photo showing the distributor with plates at the top of CMBF.

Figure 4. A screenshot extracted from a VR model showing the avatar in the hot metal tapping area. 1: Spout for tapping of hot metal; 2: Spout for tapping of liquid slag; 3: Hydraulic mud gun for injection of mass; 4: Ladle to pre-treatment of hot metal.
1.2 kg cm$^{-2}$, and the top pressure ranging from 0.15 to 0.25 kg cm$^{-2}$.

**Top gas cleaning system (TGCS)**

The virtual model of TGCS consists of dry and wet system to clean the top gas. The first equipment is an expanding balloon and the second is a wet cleaning tower with three stages (saturator, venturi and desiccant). This system, shown in Figures 1 and 2, ensures elimination of dust particles in the top gas after cleaning, satisfying the environmental legislations. The sludge from wet system is transported to a thickener and the decanted sludge then enters a press filter. In some CMBF units the filtered material is used along with other ore fines in the sintering plant.
Casting system for pig iron (CSPI)

The virtual model of CSPI is made up of two circular casting machines carousels, each containing 143 ingot moulds of cast iron, with a casting capacity of 48 t h\(^{-1}\) of liquid pig iron. Figures 1 and 2 show a vision of the CSPI in VR model.

Control room operation (CRO)

A 360° photo library of illustrative pictures of CRO from different companies is available in this project. The control room of industrial facilities consists of computers, televisions and the supervisory system of monitoring and control of operating parameters of pig iron manufacturing process. From a hyperlink one can access a 2D screen process data visualization regarding the operation of CMBF.

Laboratories, thermoelectric power plant and pulverized charcoal system

Hyperlinks for 360 photos of illustrative pictures concerning laboratories, thermoelectric power plants and pulverized charcoal injection systems have also been incorporated in the 3D model. Typical mass injection rate of pulverized charcoal in the tuyeres of a CMBF is in the range of 60–120 kg t\(^{-1}\) of pig iron. Another important aspect from the point of view of sustainability in green ironmaking is the installation of plants for generation electricity using blast furnace top gas after cleaning. There is also laboratory infrastructure for performing chemical and physical tests on mineral samples, charcoal, waste, products and byproducts.

Concluding remarks

The VR project of the CMBF can be used to train workers, technical personnel in the green ironmaking plant and also to provide technical information to visitors, students of engineering schools, researchers, equipment manufacturers etc. It is a multidisciplinary tool that contributes to improving teaching and learning techniques as well as aspects of design operation, and process control. This interaction is a breakthrough and is expected to bring about considerable benefits to both the industrial and academic sectors. Future work is planned to integrate VR technology with CFD models for charcoal blast furnaces.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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