Development of an Online Blast Furnace Burden Profile Measuring System

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Gas permeability in a blast furnace is directly influenced by the burden profile, which is the result of the charging angle collocation. An obviously increment in both iron-making productivity and furnace campaign life will be observed in a high heat utilization furnace with uniform gas permeability. An online burden profile measuring device without gas leakage risks and heavy maintaining load had been expected for a long time. But the thermal radiation, pressure and corrosive gas inside an operating blast furnace reduces both the performance and life cycle of its online instruments. Especially, intensive dust blowing in furnaces was the main problem that limited the development of online burden profile measuring technology. In this study, a special application of the radar ranging process on a compact scanning system was developed to measure the online burden profile. The innovated design in scanning successfully lowers the space requirement for system installation on the top cone of a blast furnace. Eventually, the profile discrepancy between the different sets of burden charging sequences can be compared from the online measurement results. The modulation in burden charging sequences to form a better gas permeability in a blast furnace will be consequently possible via the achievement of the developed online burden profilometer.

1. INTRODUCTION

Although some new iron-making processes have been revealed in the past decades, the blast furnace is still the most commonly employed facility for hot metal production, due to its advantages in high productivity and heat utilization. The blast furnace is a huge reactor filled with burden, high pressure blast and intensive dust, which makes it very difficult for measurement devices to survive. Intrinsically, the iron-making blast furnace is an extremely complicated process (1), because the counter current heat and mass transfer, reduction of ferrous burden by reducing gases and coke, burden softening and melting in the cohesive zone, combustion of coke and pulverized coal in the raceway, hot metal drainage through tap hole, and so on are simultaneously carried out in a single reactor. As it is operated with so little information available, the blast furnace is also known as a “black box” in the steel industry. To stabilize furnace operation and extend its campaign life, reliable sensing and measuring technologies are necessary to provide useful information to the furnace operators. However, the influence of high temperature and dusty blast in a blast furnace makes the development of measuring devices a challenge.

Among all the factors that influence blast furnace operation, burden surface profile is indeed the most important one for operators, who can modulate burden charging sequences to increase productive efficiency and reducing power resource consumption. Appropriate gas permeability in a blast furnace could be obtained from a well situated burden profile which not only increases the heat utilization but also mitigates the heat load on the furnace wall. The blast furnace operators would acquire a powerful implement to modulate the burden charging sequences via the development of a burden profilometer.

The application of most measuring technologies has been hindered by the harsh conditions in blast furnaces. Many researchers have attempted to build compact size models to analyze the burden charging process (2,3). However, the approach lacks accuracy since the model cannot be verified perfectly to match with the real burden charging situation. In order to achieve real measurements, several methods have been attempted in the past decades. Taking advantage of recent achievements in opto-electronic and semiconductor devices, surface profiling using 3D laser technology has become available with elevated speed and lower price. Such distinguishing features enable surface profile measurement at very high resolution and accuracy within a couple of minutes (4,6). However, due to the nature of the laser light, the device can only be applied at scheduled shutdowns during which time the dust intensity inside the blast furnace is much reduced. Because of their excessive wavelength, microwaves can penetrate intensive dust, and are known to be more suitable for distance measurement in the harsh environment(7). Nippon Steel has developed a 2D microwave surface profiler by mounting several antennae on a moving probe stabbed into furnace while measuring(8), nevertheless, such a configuration has enormous size and therefore increases the possibility of gas leakage during operation.

This paper presents the development of an online blast furnace burden profile measuring system. The online system overcame the adverse conditions inside a blast furnace by the compact scanning design with radar ranging technology. A compressed chirp radar pulse generator, operating in K-band with a specified horn antenna, high sensitive module and low cycle-time signal processor was composed to be the ranging device of the online system. A cooling and purging circuit was also designed in the system to balance the thermal radiation and dust contamination from the furnace. The remainder of this paper is organized as follows. Section 2 briefly explains the radar ranging principle and makes a comparison with the laser ranging technology. The development of the online burden profile measuring system is described in Section 3. The burden measurement results of the radar surface profiling system are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. RADAR RANGING TECHNOLOGY

Obtaining a surface profile at an elevated accuracy, resolution and high data throughput is always a demanding task in the research field of metrology. Many non-contact methods have been proposed for surface profile measurement in the past few decades. Various measuring principles are employed by these systems, including vision based methods, interferometry, as well as time-of-flight. Among these measurement principles, time-of-flight is the most promising technology for burden profile measurement, as it offers a extended measurement range with centimeter accuracy which is adequate for characterization of the burden surface dimensions.

The laser and microwave are two forms of electromagnetic waves that are commonly used for time-of-flight measurement, and which differ only by their wavelengths. The laser spot is much smaller due to its short wavelength nature, and therefore a better measurement resolution can be expected. On the contrary, the microwave has a relatively larger beam area, resulting in a rather unattractive feature for surface profiling as it is unable to capture detailed geometries during the scanning process. One overwhelming benefit offered by the microwave is its superior particle penetration property in an environment of high dust intensity, especially during blast furnace operation where the material powders are stirred by the up-rising hot blast.

A detailed comparison between the laser and microwave in terms of measurement specifications is listed in Table 1. However, the laser device can only be applied at scheduled shutdowns at which time the dust intensity inside the blast furnace is much lower. The intensive dust blowing in an operating blast furnace highly influenced the measurement results of a laser distance measuring device. Furthermore, the ultrasonic waves are critically influenced by the temperature, pressure, and density of medium, which is not suitable to apply in burden profiling.

James Clark Maxwell predicted the existence of radio waves in his theory of electromagnetism as long ago as 1864. He showed mathematically that all electromagnetic waves travel at the same velocity in free space, independent of their wavelength. Heinrich Rudolf Hertz, verified Maxwell's theory by experiments carried out in 1886-87. The velocity of an electromagnetic wave is the product of the frequency and the wavelength. The electromagnetic waves have an electrical vector $\underline{E}$ and a magnetic vector $\underline{B}$ that are perpendicular to each other and perpendicular to the direction of the wave. The electrical vector has the major influence on radar ranging applications. Radar altimeters developed in the 1930s use a form of radar called FM-CW or Frequency Modulated Continuous Wave radar. In the 1970s, the same FM-CW measurement technique was

Table 1 Comparison of laser and microwave performance

	Laser	Microwave
Wavelength	900 nm	5.2cm (5.8GHz)
Accuracy	20 mm	30 mm
Resolution (at distance 10m)	7mm	50cm
Cycle time	30 ms	500ms
Dust penetration	Poor	Excellent

used in the production of the first radar ranging tank gauge. In the late 1980s, pulse radar ranging transmitters were developed for process measurement applications. Figure 1 shows the electromagnetic spectrum in the range of frequencies and wavelengths from electric waves to gamma rays. A commonly used range of a radar ranging transmitter is between 5.8 GHz (5.2cm) and 26 GHz (11.5mm).

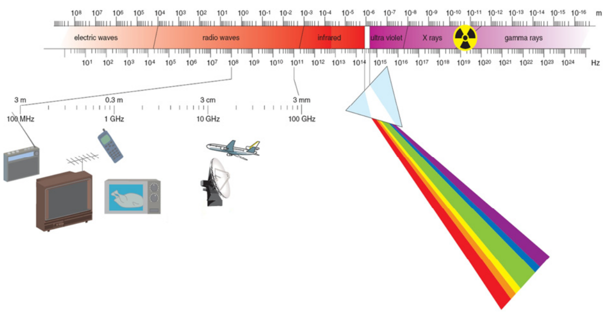

Fig. 1. Electromagnetic spectrum.

Process radar ranging transmitters operate at microwave frequencies between 5.8 GHz and about 26 GHz. Researchers have chosen different frequencies for reasons ranging from licensing considerations, availability of microwave components and the perceived technical advantages. The higher the frequency of a radar ranging transmitter, the more focused the beam angle for the equivalent size antenna, but lower frequencies are not adversely affected by high levels of dust or steam. In steamy and dusty environments, higher frequency radar will suffer from increased signal attenuation. As shown in Fig. 2, a measure of how well an antenna is directing the microwave energy is called the 'antenna gain' which can be calculated as:

$$G = \eta \times \left(\frac{\pi \cdot D}{\lambda}\right)^2 \quad \text{...} (1)$$

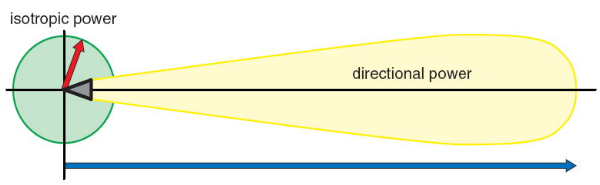

Fig. 2. Illustration of antenna gain.

where η is aperture efficiency, D is antenna diameter, and λ is wavelength. It is clear from Equation 1 that a larger antenna has a narrower beam angle at a given frequency. Also, we can see that the antenna gain and hence directivity is inversely proportional to the square of the wavelength. For a standard horn antenna, the beam angle φ, that is the angle to the minus 3 dB position, can be calculated using Equation 2. Figure 3 shows horn antenna diameter versus beam angle for the most common radar frequencies, 5.8 GHz, 10 GHz and 26 GHz. In the application of the online blast furnace burden profiler,

$$\varphi = 70^o \times \frac{\lambda}{D} \quad \text{..} (2)$$

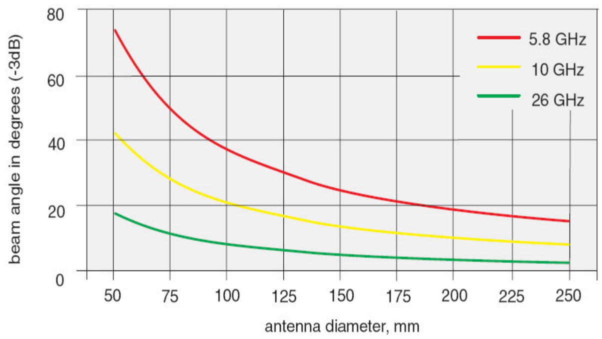

Fig. 3. Relation between horn antenna diameter and beam angle.

High temperature or large temperature gradients have very little effect on the transit time of microwaves within an air or vapor space. As shown in Fig. 4, at a temperature of 2000°C the variation is only 0.026% from the measurement value at 0°C. Radar ranging transmitters with air or nitrogen gas cooling are widely used in molten iron and steel applications.

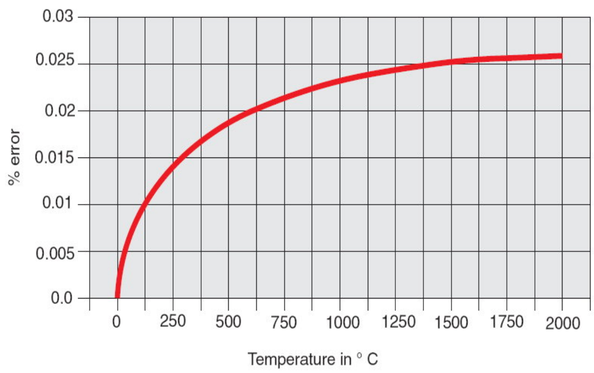

Fig. 4. Temperature effect on radar measurement of air at a constant pressure of 1 Bar.

Pressure does have a small but more significant influence on the velocity of electromagnetic waves. As shown in Fig. 5, at a pressure of 30 Bar, the error is only 0.84%. However this becomes more significant and at a pressure of 100 Bar there is a velocity change of 2.8%. If the pressure is varying constantly between atmospheric pressure and 100 Bar, the velocity variations can be compensated using a pressure transmitter.

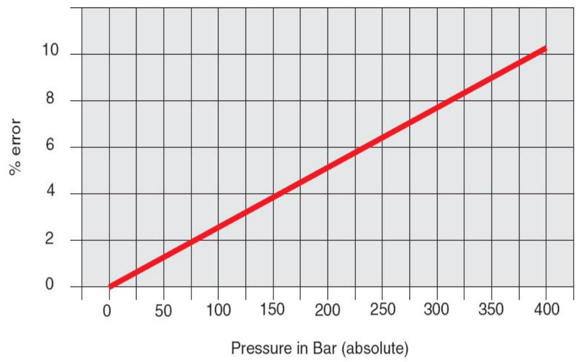

Fig. 5. Influence of pressure on radar measurement in air at a constant temperature of 273 K.

Fig. 6. An existing online burden profilometer at CSC.

3. DEVELOPMENT OF THE ONLINE BURDEN PROFILE MEASURING SYSTEM

A special project to develop the online blast furnace burden profile measuring system was created in 2005 at China Steel (CSC). The scheming measuring technology was laser in origin, due to its improved dust filters announced in recent years. A prototype based on the laser distance measuring technology was created and installed on the No.1 blast furnace at CSC. But the efficacy of these dust filters was not yet enough to overcome the influence of the intensive dust blowing in an operating blast furnace. Radar ranging, operated at a microwave frequency, was finally adopted for its excellent dust penetrability to be the kernel measuring technology in the online burden profilometer development project.

The burden profile is essential for the blast furnace operation to ascertain the status of the furnace, and thus to determine if the charging sequences have to be modified. Two lance type burden profile measuring systems developed by Nippon Steel were sequentially installed on the No.3 and No.4 blast furnaces at CSC in 1998. As shown in Fig. 6, the Nippon Steel burden rofilometer stabbed into an operating blast furnace while measuring with a moving probe mounted with several antennae. As a result, a two-dimensional burden profile along a specified radial direction could be drawn; nevertheless, such a configuration has an enormous volume, which results in a heavy duty load on maintenance, and therefore increases the possibility of gas leakage during operation. The pressure value inside the top cone of a blast furnace where the probe was stabbed in is about 2 to 2.5 bar. Now, at CSC, after one emergency shutdown at the No.3 blast furnace caused by a serious gas leakage from the gate after probe stabbing, the utilization of these two profilometers has been limited.

Gas leakage and enormous volume are fatal disadvantages that must be avoided in the development of an online burden profilometer. A brand new configuration to apply radar ranging technology to burden profile measuring has to be worked out. As depicted in Fig. 7, a motorized compact scanning system design has finally been carried out in the study. In consideration of system protection and gas leakage prevention during its operation, the measuring system is designed to direct the microwave energy by an antenna radiated into the blast furnace through a small opening on the wall. In such a configuration, a ball bearing installed on an aperture serves to isolate the equipment from the hot and dusty gas. A high directivity horn antenna is mounted on one side of the ball bearing, guiding the microwave energy into the blast furnace. The scanning is performed by controlling the tilt angle of the microwave beam, so that the spot illuminated by the beam is able to scan across the burden surface. A large scanning range of ±35 degrees was achieved, enabling the feature dimensions of the burden profile to be captured by the system. The whole system is packaged inside a closed unit as seen in Fig. 7, and purged with high pressure air flow to keep the hot blast out of the enclosure.

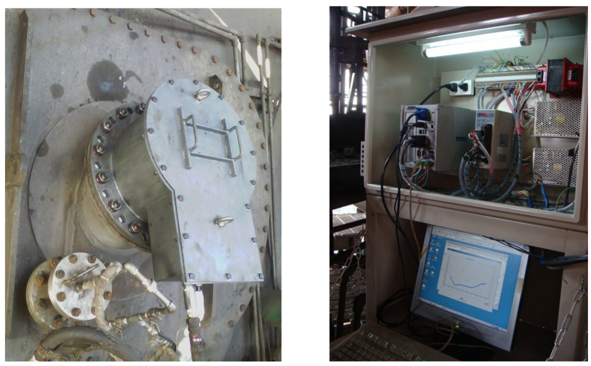

Fig. 7. Newly developed online burden profilometer at CSC.

To perform real-time surface profile scanning, an automatic program was developed to servo the radar device to different tilt angles while receiving the range data at the same time. The program performs three tasks during scanning. First, it receives the signals of charging information from the process controlling system and sends out the command to drive the positioning system so as to move the radar device, and records the position at every single measuring point. Second, the program receives the digitized range data and performs averaging so as to reduce measurement uncertainties. Third, it converts the positions into sensor tilt angles. Afterwards, a coordinate transformation is carried out to generate the burden surface profile. The human machine interface of the online profilometer was set up in a furnace control room for the operators who can remote control the client automatic program activated to make a burden profile scanning. The burden level descending rate can be evaluated from twice profile scanning in the same charging interval. The cycle time of the burden profiling depends on the number of measuring points. Using CSC's newly developed burden profilometer, it takes about 45 to 50 seconds to finish one scanning process.

After a long period of operation, the components inside the online burden profilometer may be out of order. Moreover, as an operating blast furnace is a pressured vessel, and the profilometer is interlinked to it, the online maintaining process will not be sufficient. If the toxic gas inside an operating blast furnace leaks out, it will cause fatal injuries to the workers and maintainers. So the maintenance of the online burden profilometer can only be carried out at regular shutdowns. Therefore, some intelligent driving modes have to be embedded to avoid any online profilometer malfunction caused by the over use of inactive components. For example, under the blowing effect of the cooling system, an online burden profilometer becomes a relatively cool spot on a blast furnace. This causes the hot dust in the blast furnace to congeal on the contact area of the burden profilometer and to form concretion on its surface. The concretion produces an additional resistance to the driving system of the online profilometer. A cleaning mode triggered by a motion monitoring loop of the driving system with transient high torque output was accordingly developed to scrape the concretion.

4. MEASUREMENT RESULT

The developed online burden profile measuring system has been installed on No.1 and No.3 blast furnaces at CSC since 2007 to carry out real measurements during the operation. The installation socket for the online burden profilometer can be an existing and modified manhole at lower altitude with a narrow scanning angle, or a newly drilled opening at higher altitude with a wide scanning angle after FEM structure strength simulation. The online profilometer at the CSC No.3 blast furnace was installed on an existing manhole. Due to the manhole dimension limits, this one could only obtain the half burden profile on its specified radial direction. But the online profilometer at the CSC No.1 blast furnace was installed on a new socket designed for the system.

Since the signals of a radar ranging device take a considerable time to stabilize at every measuring point, the burden profile was composed of limited scanning points. A polynomial fitting method was adopted to produce a curve represented as the measured burden profile from the measuring points. Figure 8 shows the early burden profile scanning result at the CSC No.3 blast furnace. The cross section shows a deep V-shape burden profile with its level varying from SL-1 meters at the side to SL-3.5 meters at the center, without an obvious terrace around the wall. The pulverized coal injection (PCI) rate of the CSC No.3 blast furnace during the measuring period was about 130 kg/tHM and the molten iron productivity was about 8200 ton/day.

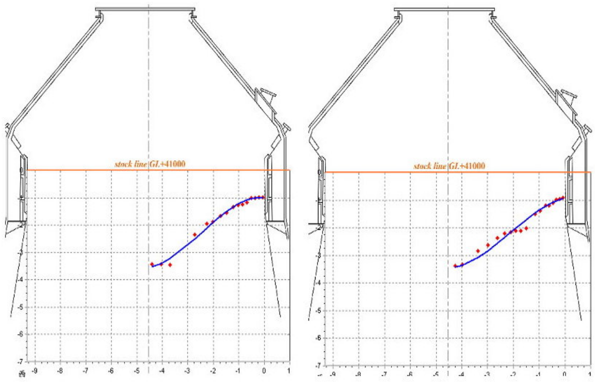

Fig. 8. Early burden profile scanning result in the CSC No.3 blast furnace.

The desired burden profile theoretically should be M-shaped with an obvious terrace around the wall, and the level difference between the periphery and the center should be below 2 meters. Figure 9 shows the later burden profile scanning result in CSC No.3 blast furnace. The operators changed the charging angle to form a better burden profile based on the measurement results of the developed online profilometer. The PCI rate of the CSC No.3 blast furnace during this measuring period was stably raised to 180 kg/tHM and the molten iron productivity was also raised to 8600 ton/day. Figure 9 also shows the burden descending rate evaluated by the polynomial fitting curves from the difference of the two burden profile measurements in one charging interval. Three regions separated from the same cross-section area were used to represent the burden descending rate from periphery to center.

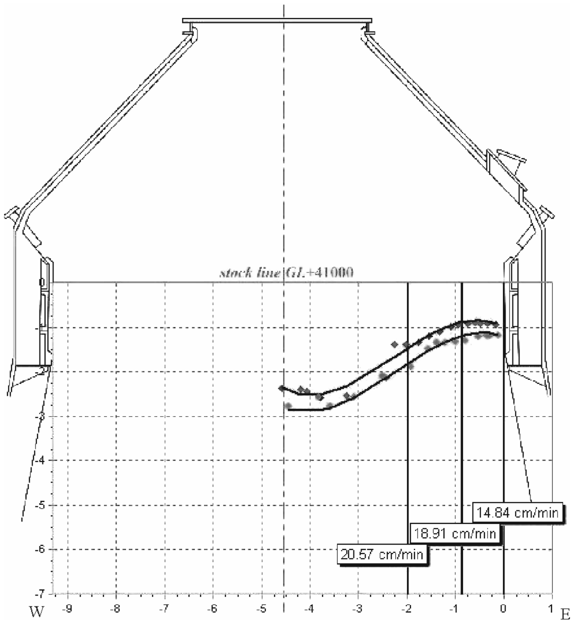

Fig. 9. Later burden profile scanning result in the CSC No.3 blast furnace.

5. CONCLUSIONS

An online burden profile measuring system without enormous volume, heavy maintenance load and gas leakage risks was successfully developed at CSC. Both laser and radar ranging technology were tested in the project. The radar ranging technology, operated at microwave frequency, was finally adopted for its excellent dust penetrability to be the kernel measuring device in the online burden profilometer. A remote controlled framework was set up to help furnace operators manipulate the online profilometer in the control room with other useful messages nearby. Some intelligent driving modes were developed to avoid the malfunction emergence of the online burden profilometer caused by the inactive components after a long period of operation. A conspicuous improvement in the CSC No.3 blast furnace productivity by the change of the charging sequences based on the measurement results from the online profilometer was obtained.

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