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A Survey Study of the Blast Furnace at Kuangshan Village Using 3D Laser Scanning

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The blast furnace from the Northern Song Dynasty at Kuangshan Village is the tallest blast furnace that remains from ancient China. Previous studies have assumed that the furnace had a closed mouth. In this paper, a three-dimensional (3D) model of the blast furnace is constructed using 3D laser scanning technology, and accurate profile data are obtained using software. It is shown that the furnace throat is smaller than had been previously thought and that the furnace mouth is of the open type. This new furnace profile constitutes a discovery in the history of iron-smelting technology.

INTRODUCTION

Iron smelting technology was well developed in ancient China. Early in the sixth century B.C., the Chinese were able to produce cast iron using blast furnaces. The use of a blast furnace to smelt iron can separate slag from molten iron and produce iron products rapidly, which is a significant advantage. The furnace profile is the core of blast furnace iron-smelting technology. It plays a key role in the efficient smelting of pig iron and has rich technical content. As a result of the traditional artificial method of surveying and mapping, data on blast furnaces are often missing or lacking in the relevant research.

In recent years, a new method of high-resolution surveying and mapping provided by three-dimensional (3D) laser-scanning technology has been used in cultural heritage research, for example, in cave temples and ancient buildings,[1] the Shuiquangou iron-smelting site in Beijing, which dates to the Liao Dynasty (A.D. 916–1125),[2,3] and the Jiudian iron smelting site in Henan, which was built during the Warring States Period (475–221 B.C.).[4]

In this article, a blast furnace that was built during the Northern Song Dynasty (A.D. 960–1127) was investigated at Kuangshan Village, Wuan, in Hebei. The process of 3D scanning and information extraction is introduced. This process is emphasized because it is a newly discovered method for the study of ancient furnace profiles that can be better understood using scan results. It also expands the understanding of complex smelting processes and the skill of ancient artisans.

A Brief Introduction to the Furnace at Kuangshan Village

Wuan is located in Handan, Hebei Province. This area is rich in iron mineral resources and is an important centre for iron-making. There are many skilled iron-smelting artisans. Several ancient blast furnace sites have remained.

The subject blast furnace is located in a farmer's yard that is approximately 15 km from Wuan (Fig. 1). It is considered the tallest surviving ancient blast furnace in China. This furnace is the best evidence of China's metallurgical technology during that period. There are four effective ^{14}C dates from charcoal samples that were extracted from the furnace wall. These dates show that the blast furnace was in use from A.D.810 to A.D.990 (with a 94.4% probability), which spans the Tang and Northern Song Dynasties.

At present, the blast furnace is approximately 6.4 m high. Half of the furnace wall remains. The section of furnace wall is composed of four layers. From the interior to the exterior, the first layer is adhering slag, the second layer is made of stone and approximately 0.8 m wide, the third layer is rammed earth, and the fourth layer is made of stone. The top of the blast furnace is composed of

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sharp rocks. The upper section of the blast furnace is composed of cobblestone, which is embedded in the wall. The lower section of the blast furnace is composed of cement, which is part of the modern reinforcement. The inner diameter of the bosh is approximately 3.0 ms. The furnace wall has been significantly corroded, the furnace lining has been completely burnt, and a slag skull has formed. To the right side of the bosh, half of the furnace wall has been corroded. The body of the furnace is upright, and the mouth is slightly open. The air inlet is located at the centre of the bosh, which is approximately 0.5 m taller than the hearth. The tuyere has been removed and filled with cement.

Fig. 1. The current situation of the Kuangshan Village blast furnace.

Scholars have investigated this blast furnace site since the 1950s. Based on an unsharp picture of the blast furnace, Liu Yuncai thought that the furnace profile was closer to that of a modern furnace. The shaft and bosh angles were prominent, and it had a smaller mouth, which is a typical furnace profile (Fig. 2a).[5] This view has been referenced in the history of metallurgy,[6,7] and of the Song Dynasty[8] for many years.

The stack angle is the angle between the bosh and the furnace body, and is crucial for iron smelting. According to existing research,[5,6] the stack angle helps reduce heat loss and controls the furnace charge's thermal expansion and contraction. The bosh angle helps reduce heat loss in the hearth. When the furnace burden burns down, the temperature of the blast furnace increases, the volume of the furnace burden expands, the pressure on the furnace wall increases, and the friction between the furnace burden and the furnace wall increases. If the furnace body is tilted inward, the friction between the furnace burden and the furnace wall is reduced. This design prevents the furnace burden from hanging on the furnace wall and thereby reduces damage to the furnace lining, which is beneficial to the running furnace burden. At the same time, the furnace body is tilted inward, which aids in ore reduction.

During the Song and Liao Dynasties (A.D. 916–1279), blast furnaces in the north generally had stack angles. Their shaft angles were built of stones,

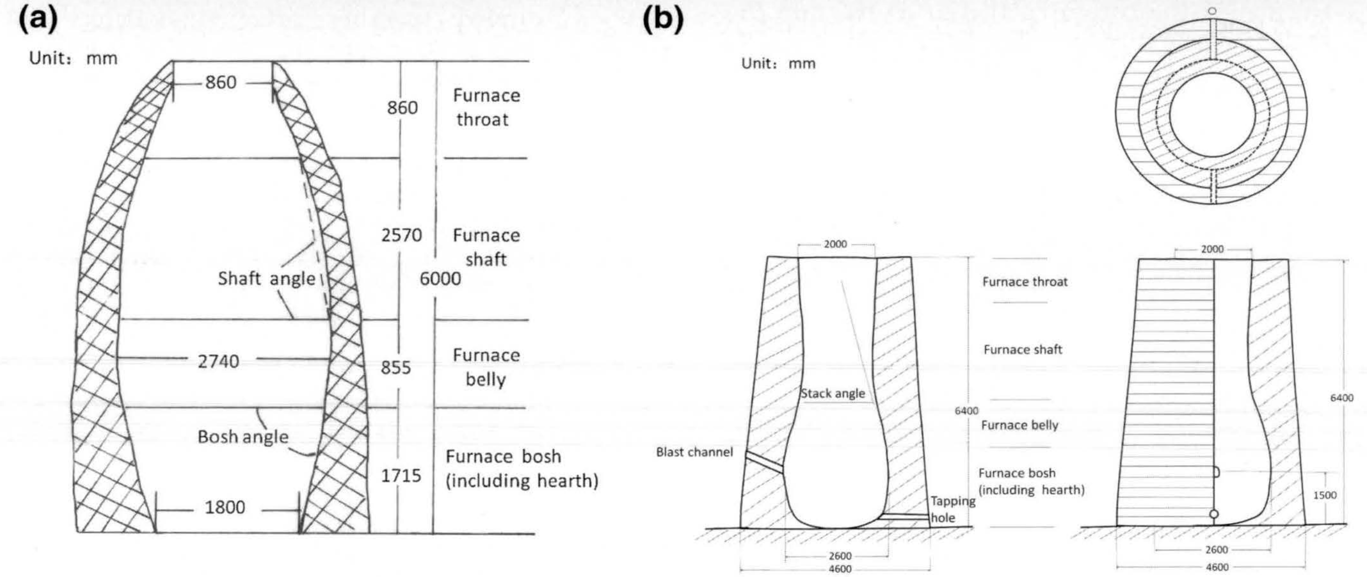

Fig. 2. (a) Repainted according to Y. C. Liu.[5] (b) A simple map of the reconstructed shape of the furnace. The difference is the furnace profile.

which effectively improved the intensity of these blast furnaces, e.g., the blast furnace at Maijiehe, Jiaozuo in Henan from the Song Dynasty (A.D. 960–1279) and the blast furnace at Dazhuangke, Yanqing in Beijing from the Liao and Jin Dynasties (A.D. 916–1234).

The authors believe that the profile of the Kuangshan Village furnace is not of the closed type and that it represents a later development. This view has not been put forward in previous studies. Since 2009, the authors have visited and investigated the Kuangshan Village iron-smelting site three times. By careful observation, the authors found that the inner diameter does not become continuously smaller from the middle to the top of the blast furnace; instead, it is open, which creates the appearance of a hopper. The authors have reconstructed the furnace profile using to the findings of previous articles (Fig. 2b). To confirm this theory, the Kuangshan Village blast furnace was scanned using 3D laser-scanning technology.

The Process of Three-dimensional Laser Scanning

Three processes were used to image the Kuangshan Village blast furnace with 3D laser-scanning technology: a work plan was formulated before scanning, the data were collected during the scanning process, and the data were processed after scanning.

1. Formulating a work plan based on the scanning environment. The selection of a 3D scanning device depends on the specific situation of the object and its surrounding environment; once a device has been identified, a scanning scheme can be formulated. On the basis of the field environment of the blast furnace in Kuangshan Village, the factors that needed to be considered included the height of the furnace, the size of the bottom of the structure, and the texture of the furnace body. Ultimately, a FARO laser scanner was selected. The FARO-Focus^{3D}X330 is a high-speed 3D scanner,[9] which can scan long distances over a wide range. In sunlight, it is usable at a distance of 330 m. Integrated GPS receivers were used to interconnect every scanned and post-processed image and to simplify measurement and processing.
2. Collecting the object data during the scanning process. The clutter was cleared from around the blast furnace to reduce interference. The internal wall of the blast furnace is exposed to the outside, and part of the bottom connects to the villagers' living quarters. The blast furnace is surrounded by a circular iron handrail. Based on the size of the furnace body and the surrounding environment, there are 11 possible scanning points in different scanning areas. A mutual target between two scanning points was configured around the bosh to avoid the establishment of a straight line, because there should never be fewer than three scanning points. The scanning process was as follows:
   1. Place the target.
   2. Set up the scanner. The point cloud data are all collected at this scanning point. Move the scanner to the next scanning point until the full scan is complete.
   3. Photograph the blast furnace from different angles with a digital camera. The more photographs, the more details can be rendered during post-processing.
3. Post-process the scanning data.

FARO SCENE,[9] Geomagic Studio,[10] and Maya from Autodesk[11] have been used for the post-processing stage of the 3D laser-scanning process. The data processing process is as follows:

1. Establish a project and import the cloud data from the 11 scanned points into FARO SCENE. The data need to be stored before the scan is pre-treated. These cloud data are derived in "plane view," which is set to the XYZ form. Geomagic Studio is used after all the data have been collected.
2. The point cloud data are de-noised and simplified using Geomagic Studio, with elements such as fences, plants, houses and other miscellaneous points excised from the original data. All the point cloud data are stored in a file. Some of the point cloud data are easy to identify to ensure that they can be deleted manually, whereas other point cloud data must be mechanically deleted as an "in vitro isolated point". The point cloud data are sampled together after de-noising. The number of scanning points is reduced, which improves the speed of data processing and operations (Fig. 3a).
3. Encapsulation and model transformation. The transformation of the triangular mesh used in the model was implemented directly by "encapsulation" in Geomagic Studio. The blast furnace model's appearance was preliminary. At this stage, there were some holes in the blast furnace model. The surface of the furnace body was meshed coarsely, which meant that some of the point cloud data were missing. The holes in the model were repaired using the "curvature fill" function (Fig. 3-b). Finally, the model was processed using a "network doctor". Some mistakes, such as nail materials and other defects, were corrected, and the 3D model of the blast furnace was finalized (Fig. 3c).

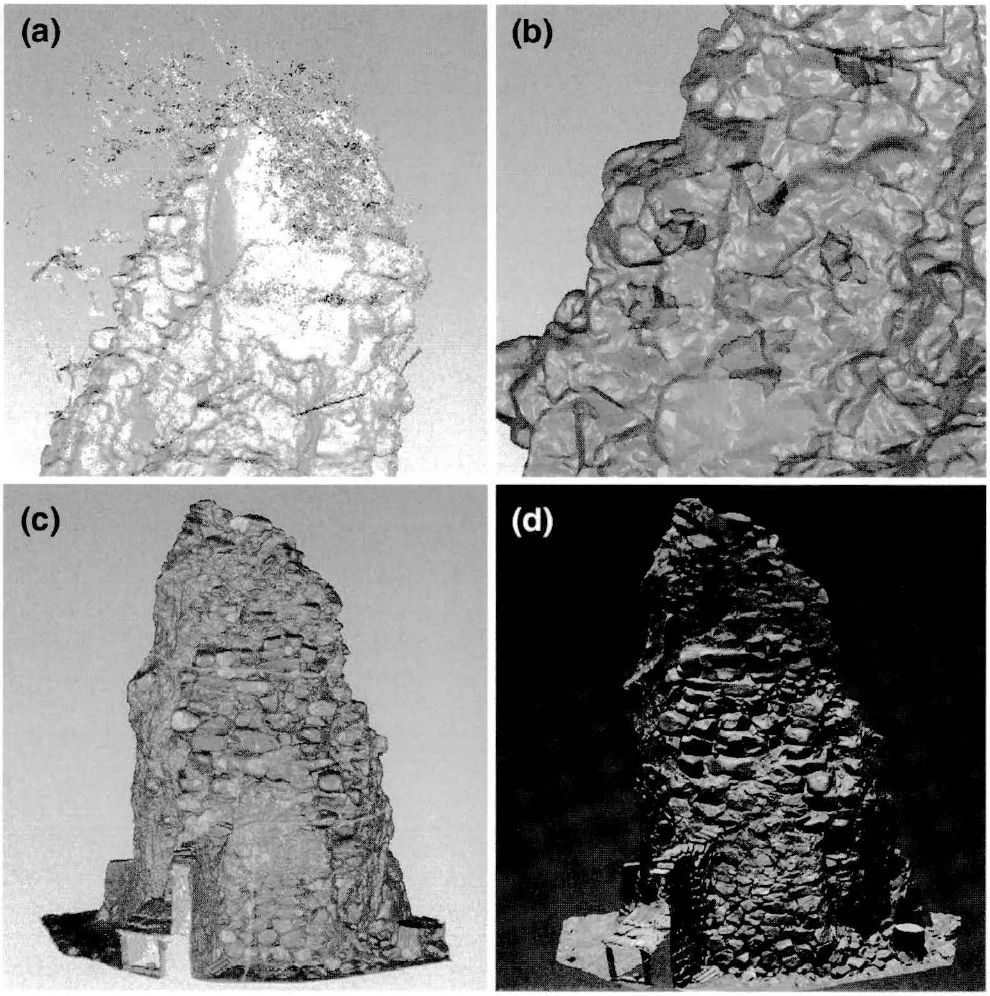

Fig. 3. (a) Some of the point cloud data outside the blast furnace. (b) The filled holes in the model. (c) The 3D model of the blast furnace. (d) Texture mapping.

4. Texture mapping of the 3D model of the blast furnace using Maya from Autodesk. In the previous step, the 3D model of the blast furnace was created; however, the colour of the furnace body was not reflected. Colour information can be represented using texture mapping. The colours of photographs can be altered by the lighting when digital cameras are used in the field. These photographs need to be adjusted for their colours to be consistent. Because of the uneven surface of the furnace body and the surrounding environment, texture mapping of the photographs was performed in a small range at first because distortion can occur when a larger range is used (Fig. 3d). Texture mapping was used to more truly and accurately record and display the condition of the blast furnace. A 3D model does not need to incorporate texture mapping if the goal is only to measure the morphology of the object.

Analyzing the Model of the Blast Furnace

The 3D model of the Kuangshan Village blast furnace can be observed and measured from different angles using computer software (Fig. 4).

Based on the data from the 3D laser scanning, particularly those collected from the perspective of the longitudinal section of the tuyere (Fig. 5), the blast furnace can be identified as of the open type. The furnace body is short, and the throat is long and appears to be a large hopper. It differs obviously from other blast furnaces, and it is the earliest blast furnace with a large hopper. Therefore, the view and visual reconstruction of the furnace type is confirmed.

Early in the sixth century BC, Chinese were able to produce cast iron which could be used in the area of farm tools and weapons by using blast furnaces. Since the Han Dynasty (202 B.C.–A.D. 220), the volume of blast furnaces was close to 40 m^{-3}. Moreover, the furnace profile and blast system underwent a great change and high efficiency in the Liao Dynasty (A.D. 916–1125) and the Song

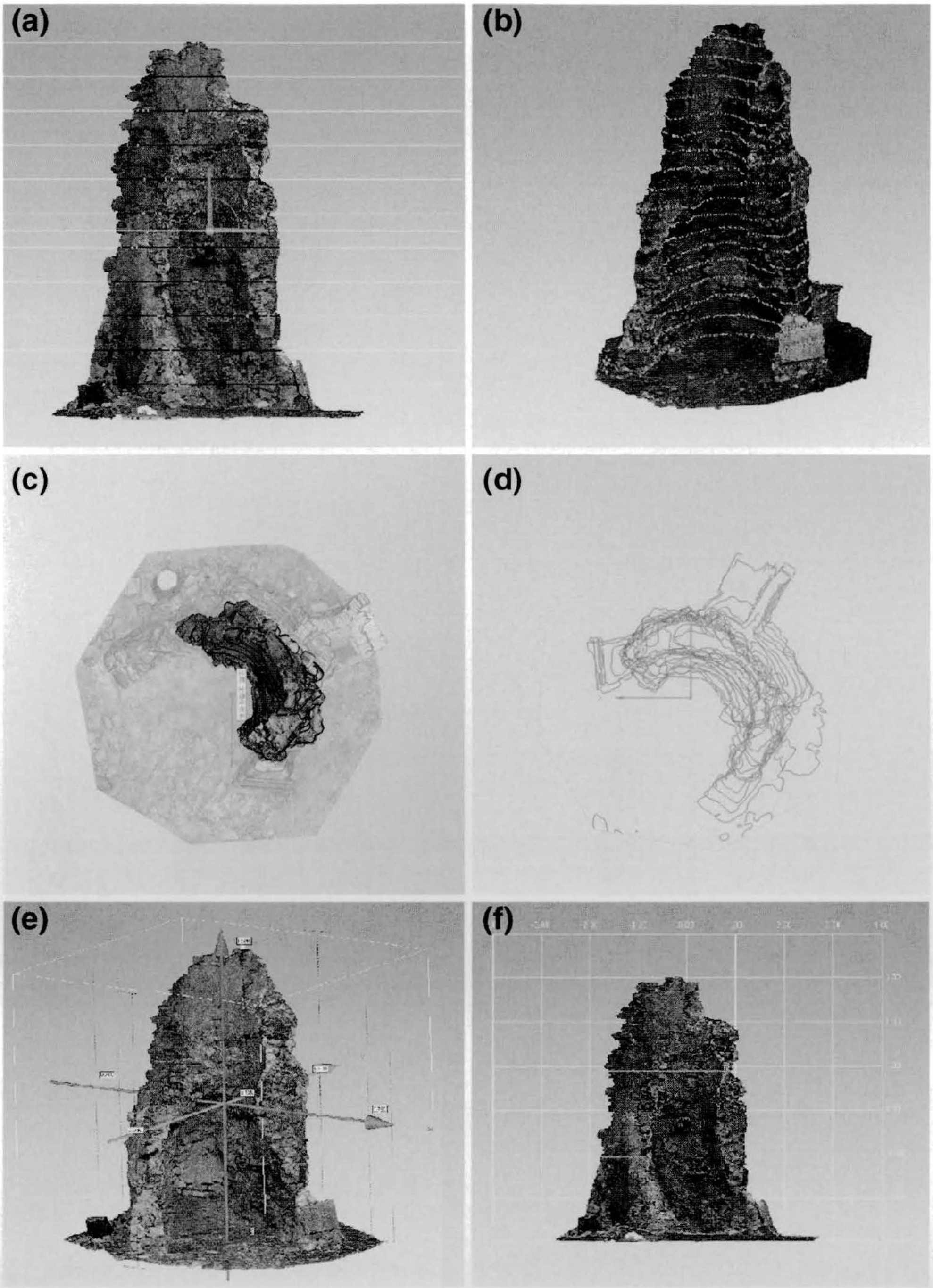

Fig. 4. (a), (b) The cross-section of the blast furnace model. (c, d) The planform of the blast furnace model. (e, f) Measuring the blast furnace model in the XYZ coordinate system.

Dynasty (A.D. 960–1279) with the continuous development of technology. The Kuangshan village blast furnace was an outstanding example of iron-making technology in the Song Dynasty with a tall furnace body and elegant furnace profile.

Wuan is one of the traditional steel centres that are located in the North China Plain. There are rich iron mineral deposits in this area. Wuan used to be an economic centre that was near the capital of the Northern Song Dynasty. During that period, there were many highly skilled iron-smelting artisans. The unique design of the blast furnace is neither arbitrary nor accidental. The technology should be further analysed through studies of its tuyere, fuel and other smelting components.

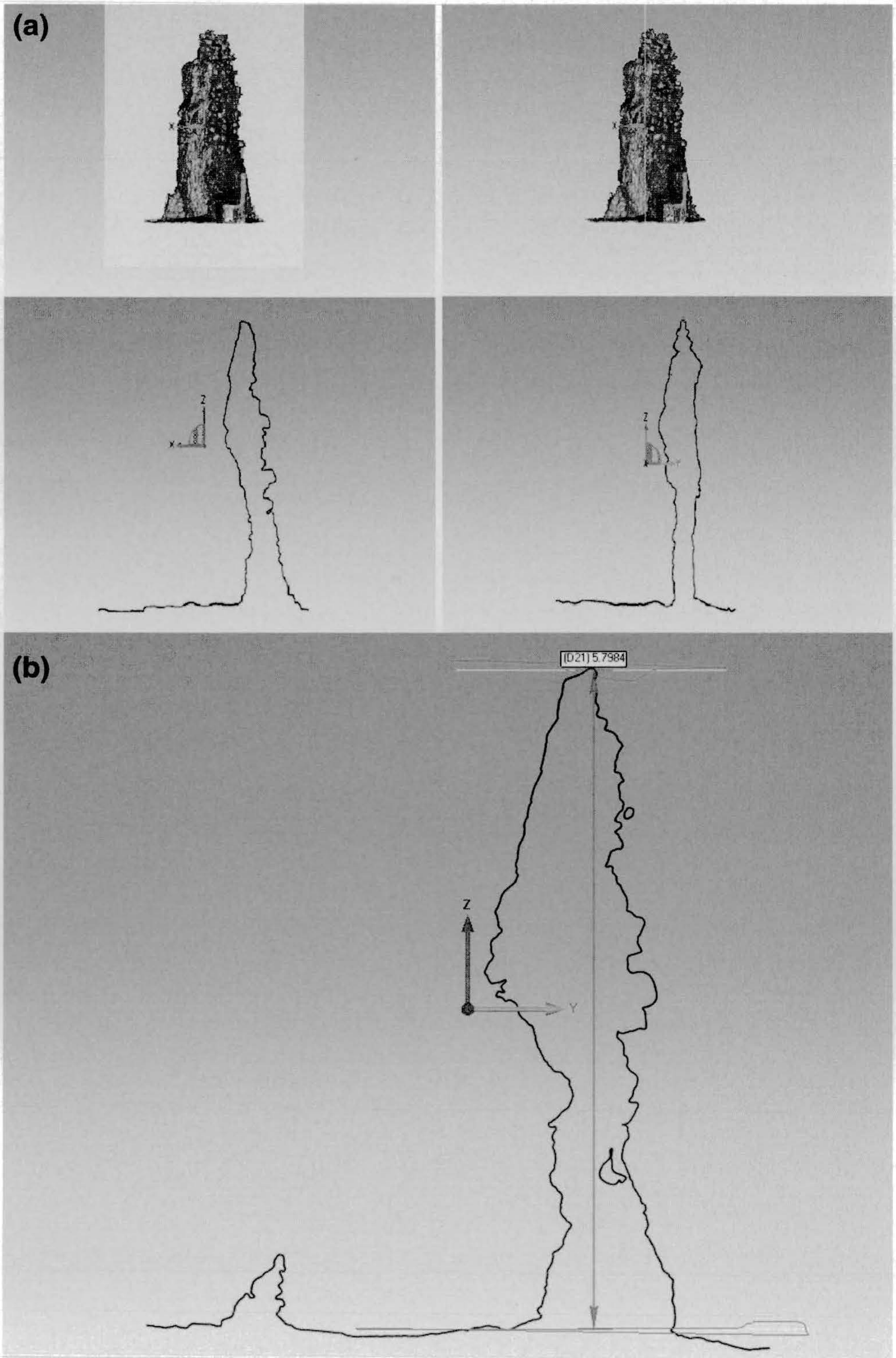

Fig. 5. (a) A longitudinal section of the blast furnace model. (b) A longitudinal section of the tuyere.

CONCLUSION

In this article, based on data that were obtained from 3D laser scanning, an accurate shape for and precise data on the Kuangshan Village blast furnace have been obtained. To collect and display multi-angle observations, all the details of the blast furnace were extracted. This process surpassed the traditional method of surveying and mapping by providing specific reference data for some of the damaged parts of the blast furnace. The results of previous reconstructions have been revised using the 3D model. This view shows that the Kuangshan village blast furnace is clearly different from other blast furnaces, while, at the same time, it has a unique type of profile. This survey provides new evidence for the study of iron-smelting technology in ancient China. A new method for archaeological surveying and mapping using 3D laser-scanning technology is provided.

With the development of surveying and mapping technology, 3D laser-scanning technology provides a faster and more accurate non-contact solution. It also offers more information and perspectives for research on ancient iron-smelting sites than do the traditional methods. Based on the technological merits described above, this technology should be applied more broadly in the conservation of cultural heritage and archaeological work.

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