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Invention of cast iron smelting in early China: Archaeological survey and numerical simulation

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ABSTRACT

The earliest cast iron in China dates to the 8th century BC and pre-dates the earliest European evidence by about two millennia. The invention of cast iron smelting is closely related to the pre-existing and contemporary technologies of casting bronze and firing ceramics as well as the social and political context of early 1st millennium BC China. A series of early iron smelting furnaces were surveyed, excavated, and scientifically analysed. However, in order to understand how cast iron was initially produced, the evidence from one of the earliest production sites was digitally simulated. This modelling allowed different potential methods for the underlying production technology to be evaluated. The explanation for the invention of cast iron lies both in borrowing and developing of techniques found in other contemporary pyrotechnologies as well as a contemporary systemic philosophical approach.

Introduction

The independent invention of cast iron production in China in the 8th century BC predated the earliest European evidence of cast iron production by about two millennia. The earliest cast iron pieces were found in Tianma-Qucun 马-曲村 cemetery in Shanxi山西 province, dating to the 8th century BC (Han, 2000) and in a tomb in Liuhe六合 county in Jiangsu province, dating to the mid 8th century BC (Nanjing, 1974). The microstructures of the artefacts showed that they were white cast iron, which was too brittle to use on a large scale. It was not until the 5th century BC that the innovation of an annealing process allowed the brittleness of cast iron to be decreased as demonstrated by the adzes and hoes excavated at Luoyang洛阳in Henan 河南 province, comprising white cast iron in the core with the decarburized layer of steel on the surface (Han, 2013). Although the beginning of iron technology in China is still an issue far from clear, the invention of cast iron production occurs after the introduction of iron bloomery production into northwest China probably from the Eurasian steppe. This is evidenced by an iron bar excavated from Mogou磨沟 cemetery, Lintan临潭 county, Gansu甘肃 province made from carburized bloomery iron and shaped by forging, dating to the 14th century BC (Chen, 2013) as well as the bloomery iron artefacts unearthed from Yanbulake 焉布拉克 cemetery at Hami哈密, Xinjiang新疆 region, dating to c.1300 BC (Qian, 2002). These dates are contemporary with the earliest iron objects and iron bloomery production in Europe (Pleiner, 2000), which presents a fundamental question. Why and how was cast iron technology invented and developed in China so much earlier than in Europe?

Cast iron is a high carbon iron alloy produced mostly in blast furnace with a wide range of compositions, which are defined as containing more than 2.1%, and usually less than about 4.5% carbon. It will be made whenever a bloomery furnace smelting iron ore is operated with too low a ratio of ore to carbon in the charge for the combustion air rate. Steel made by decarburising cast iron is more durable than bloomery steel because it contains fewer inclusions, and the productivity of the blast furnace is much greater than that of the bloomery furnace. As the carbon content of iron is increased, its initial solidification temperature decreases, for example, at 2.1% carbon it is 1380°C and at 4.3% carbon 1150 °C, the latter being not far above the melting point of copper at 1083°C. Solidification takes place in two different modes. One is as white cast iron that contains the carbon entirely as the compound iron carbide (cementite), which is hard and brittle. The other is as grey cast iron caused by the sufficient quantity silicon helping the carbide to decompose during solidification to carbon as graphite and ferrite, which is strong and little ductile. If white cast iron containing a moderate content of silicon is heated and held at temperatures between 800 °C and 1000 °C in an atmosphere low in oxidizing potential, such as in a closed container, the primary cementite decomposes into iron and free carbon (Rehder, 2000). Annealing the cast iron – a process practiced in China from at least the 5th century BC – greatly facilitated the production of tools and weapons.

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This paper presents not only an archaeological survey of the evidence for early cast iron production in blast furnaces, but also a simulation model analysing the distribution of the fluid and the temperature to explore how this invention was achieved. It also explores the relationship between cast iron and the pre-existing and contemporary pyrotechnologies relating to ceramics and bronze in China.

The reasons of the invention of cast iron

Social demands are the main reason why an invention was developed in a large scale. The increasing population pressure needs more developing agriculture and military technology and materials.

The early invention of cast iron smelting and the subsequent innovations, including fining, puddling and a range of other techniques, meant that iron production and trade had a very different economic and political significance in China from that in the West (Wagner, 2008). In the second half of the 1st millennium BC, a growing population in China combined with increasing agricultural productivity. The use of harder and heavier cast iron ploughs enabled a substantial increase and effectiveness in the ploughing of soils leading to greater productivity in agriculture.

The other main use of cast iron is in military weapons in this period of increasing conflict – those of steel could be easily and amount obtained and produced by decarburised cast iron. China was divided into several parts during the Spring and Autumn Period (770-476 BC), even in the Warring States Period (475-221 BC). The frequently happened wars between states required much more new cheap materials to replace the expensive copper and bronze weapons. Bloomery iron weapons were used in China early in 9th century, but the low productivity of bloomers had to be replaced by the cast iron smelters several centuries later, who could produce much more economic decarburised steel weapons.

Economically, iron can replace copper and become the most important metal material because the resource of iron ores is much larger amount than the other metals except aluminium in this globe (Maddin, 2002). Bronze became rarer and more expensive due to the tin minerals (cassiterite) being almost exhausted during this period, leaving cast iron to be the most important substitute. Once cast iron was invented and developed in China, it became a strategic material like salt that was not freely traded and transmitted outside for longer than a millennium, hence the cast iron technology was not transferred into Europe so easily, which might be one of the reasons why cast iron was not produced in Europe until the 13th century AD.

Besides of the social context, more technical reasons will be discussed as followed. The Chinese word *taoye* 陶冶 means to make potteries and metals, and refers also to the process by which students' and citizens' mind and characters are developed. This shows a close relationship between *tao*陶 (pottery making) and *ye*冶 (metallurgy).

The earliest evidence for the firing of pottery dates to about 20,000 BP and was found in Xianrendong 仙人洞 cave in Wannian万年, Jiangxi江西 province (Wu, 2012) and provides one of the earliest sources of evidence for pyrotechnology in East Asia. The control of the firing atmosphere is evidenced by the production of grey and black pottery at latest by 6000BC. The development of pottery firing techniques meant that there were respective kiln rooms and fire chambers, allowing the temperature to rise up to 1100 °C using the natural wind prior to 2000 BC. The innovation of a chimney on the pottery kiln in the 8th–9th century BC enabled higher temperature in the firing chamber as shown by the glazed pottery in Zhangjiapo张家坡 site in Shaanxi陕西 province where firing was demonstrated to have reached 1200 °C and therefore potentially relates to the origins of porcelain (Zhou, 1960).

However, the production of cast iron not only requires high temperatures, it also requires a blast furnace. It is in copper smelting furnaces that the technical origins can be found. The excavated copper smelting furnaces are mostly with tuyères on the lower part of the furnace wall. A shaft furnace was unearthed at Tonglushan铜绿山 site, Daye大冶 in Hubei湖北 province, dating to the 7th to 5th century BC. The reconstruction furnace size comprised 0.5 m in diameter, 1.5 m in height and about 0.3 m^3 in volume. The furnace consisted of base, hearth and bosh parts, with blowing, tapping and slag holes (Lu, 1981, Fig. 1). The different refractory layers of the furnace indicated the smelters had grasped the characters of different technical ceramics at that time. Metallurgical research on the products from the Tonglushan site showed that the cast iron prills as a by-product were involved in the copper smelting slag, which implied strongly reducing smelting conditions while probably using local chalcopyrite ($CuFeS_2$) ore. The analysis of the copper ingots found in the No. 4 furnace and the nearby Daye Lake‘¤‘§‘†‘¶‘1‘–showed there are more than 5% iron in them (Zhu, 1986). The profile of the excavated shaft furnace structure preceded the invention of the later cast iron smelting furnace.

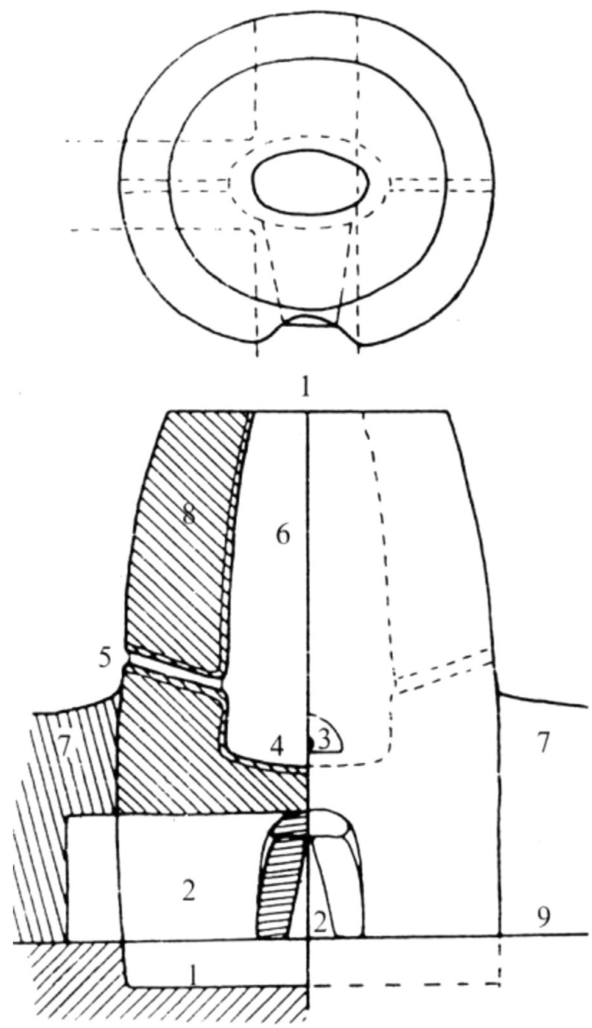

Fig. 1. Reconstruction of No. 6 furnace at Tonglushan copper smelting site (Lu, 1981) (1.Base 2. Wind tunnel 3. Metal tapping hole 4. Slag tapping hole 5. Tuyère 6. lining 7. Operation platform 8. Furnace wall 9. Original ground).

Three iron weapons with bronze or jade handles were excavated at the Guo State虢国cemetery in Sanmenxia三门峡, Henan province, dating to the 9th century BC, represent the earliest bloomery iron in central China (Han, 1998), and demonstrate the beginning of the long process for iron smelting technology, while the local copper smelting and bronze casting traditions had been developed for several centuries. A crucial connection is the tradition in copper and bronze metallurgy of pouring the molten metal into a mould. The desire to replicate this process in iron led the craftspeople to seek a kind of new metal with a relatively low melting point. Now we know the use of an iron carbon alloy with about 4% content carbon had a melting point only about 100–200 °C higher than that of copper and enabled the production of cast iron.

Annealing technology was another related pyrotechnology compacting on cast iron. It was grasped by Chinese at least in the 5th century BC. Annealing enabled cast iron to become more useful, which helped the Chinese develop the technological path of casting more easily in order to manufacture agricultural implements and tools, in contrast to the iron bloomery techniques in other civilisations. Without the annealing process after smelting, cast iron was regarded as the waste of bloomery process in the West during the first millennium BC, while the Chinese developed the cast iron foundry system under annealing technology.

Archaeological survey for iron smelting furnaces

A blast furnace is a shaft furnace in which cast iron is produced from ore. Ore, fuel (charcoal), and a flux (normally limestone) are charged periodically into the top of the shaft, an air blast is blown continuously into tuyères near the bottom, and iron and slag are periodically tapped out at the bottom. The operation continues for days, weeks, months and even years. It could be operated continuously until the furnace refractory failed. Cast iron could be obtained in simple economies with different scales of operation.

In our opinion, the key to making Chinese cast iron is in the operation of blast furnaces. It is fundamental to find more ancient blast furnaces and record the outlines of different kinds of furnaces. Although there are a few texts or illustrations describing the iron smelting furnaces to produce molten cast iron, they are too simple to be very useful and date only to the 14th century AD.

Iron smelting technology developed rapidly in ancient China, where a large amount of smelting sites have been found, though there was rarely an archaeological report on the furnaces before 1950. At the Great Leap Forward period in the late 1950s, several iron smelting sites dated before the 8th century AD were excavated, such as Tieshenggou铁生沟 in Gongxian巩县 (Henan, 1960), Xiadian夏店 site in Linru临汝 (Ni, 1960), Henan province, and Liguoyi利国驿 site in Jiangsu江苏 province (Nanjing, 1960). These blast furnaces provided preliminary knowledge for the researchers. In the 1970s, more sites were excavated such as Guxing古荥 site in Zhengzhou郑州, Wangchenggang望城岗 site in Lushan鲁山, Henan province, which yielded abundant information for ancient iron smelting (Henan, 1978). In the 1980s, a handful of furnaces at important sites including Xiping西平 in Henan province (Henan, 1994), Laiwu 莱芜 in Shandong province (Taian, 1989), Wuan武安 in Hebei province (Li, 2016, Wang, 2017), Nanzhao南召 in Henan province (Han, 2007), were excavated or archaeologically investigated. In the 21st century, a series of new smelting furnaces were found, some of which are excavated in Biyang泌阳 in Henan province (Henan, 2009), Pujiang 蒲江 and Qionglai 邛崃 in Sichuan四川 province ((Chengdu, I. 成都文物考古研究所, 2008)). There are now 167 furnaces in total mentioned in archaeological reports or articles. These furnaces were dated from the 4th century BC to 17th century AD. Some sites dating span more than one dynasty, especially in the regions where the iron ore resource was abundant, while some sites consisted of many processing workshops such as foundry and forging.

In order to explore the unknown issues surrounding iron smelting furnaces in early China, a series of field surveys were carried out with the aim of revealing new finds and new understandings. In 2009, a group of teachers and students from the Institute of Historical Metallurgy and Materials (IHMM), University of Science and Technology Beijing, started a long-term survey on the iron smelting furnaces throughout China. By the end of 2012, they investigated about 48 smelting sites, and found 13 new sites with 22 more furnaces (Fig. 2 and Table 1). Most of the sites were dated based on the typology of ceramics unearthed in context, and about one third of the sites were dated by using radiocarbon dating. Unfortunately, most of the furnaces are in a badly preserved condition, with only a few are preserved well or conserved by the government.

During the surveys, samples of tuyères, furnace materials, metals and slags were collected. Most of them were analysed in the laboratory and indicated that they were the remains of cast iron smelting, with the exception of the samples from Pingnan平南 in Guangxi广西 Region. The Pingnan furnaces were seen as bowled shape bloomery furnaces rather than blast ones. All the furnace sizes were measured carefully for the future research and reconstruction. Among them, some furnaces were accurately measured using 3D laser scanning technology. It was shown that the inner shapes of the hearth and bosh varied rapidly with the different periods and locations. Furnace materials were made of clays in Warring States Period (475-221BC) to Han Dynasty (202BC-AD220), while it changed to stones after Tang Dynasty (AD 618-907). As the demand for iron increased, furnaces slowly increased in hearth area and height, beyond the ability of human muscle to operate bellows. The section of furnaces changed from round in the Warring States Period to bigger oval ones in Han Dynasty, but round again in Tang and Song Dynasties (AD 960-1279). Another type of small furnace with square section appeared in Liao (AD 916-1125) and Jin Dynasties (AD 916-1125) in the northern China. The survey is still ongoing. Due to the complexity of the ancient furnaces, more field works and research with new technology should be carried on in the future times.

Numerical simulation: a case study of Jiudian furnace

Judian酒店 furnace at Xiping county in Henan province, dating to the middle and late stages in Warring States Period (4th-3rd century BC), was considered to be the earliest iron smelting furnace in China (Fig. 3). It was found in 1950s, and excavated in early 1990s. The furnace was built on a slope, with the base, hearth and bosh parts, and the section of the inner shape was almost round. The remains of the furnace were 2.17 m high with a diameter of 0.65–1.06 m, furnace wall width of about 0.37 m. The inner wall had glassy slag or other materials adhering to it. The base was built with charcoal powder, raw sand and clay. A small hearth angle might have been used in the furnace building. It was quite different to those huge oval Han furnaces like Guxing site. Only charcoal was used as the fuel (Henan, 1998). This furnace was in the list of the key preserved sites of National Cultural Heritage issued in 1996. The examination of the slag samples collected nearby showed that it was a cast iron smelting furnace. Scholars considered that it could produce cast iron although it was small and simple, for the followed reasons: there was a wind tunnel on the base of the furnace, which might be similar to the copper smelting shaft furnace in Tonglushan site (); natural wind from this tunnel was strong enough to help the combustion in the hearth; the wall was built with the re-cast refractory bricks, which could bear higher temperature (He, 2009).

During the field work conducted in 2012 and 2013, the furnace research team from IHMM investigated the site again and measured it with 3D laser scanning (Fig. 4). The result showed a very different aspect to the furnace (Fig. 5). A long shallow hole of about 3 cm diameter (about 8 cm at the furnace end) was found on the lower hearth part of the wall, which might be the tuyère for blowing air. The refractory had rammed clay in regular layers, instead of the bricks mentioned before. The outline of the furnace was a little different with the hand-drawing. The height of the remaining furnace is about 2.05 m, while the former handy measurement showed it was about 2.17 m.

Precise measurement of the furnace interior was the necessary first step in modelling the operating parameters of the furnace. According to the fieldwork on the other furnaces, it was thought that the wind tunnel did not exist, while the front space might have been made by removing the salamander (solidified materials in the hearth of a blast furnace below the tap hole) out of the blast furnace. The only blowing air was blast from the newly found wind hole horizontally. It should be the tuyère. Then the problem arose. What kind of furnace was used at that time: bowl or shaft? It could be numerically simulated by the software Fluent on the basis of communicational fluid dynamics (CFD). Having calculated the pressure and velocity with the airflow delivered

Table 1
Ancient iron smelting sites found in China (475 BC- AD 1644).

No.	Site	Location	Dynasty	Furnace number	Resurvey	New finding
1	Jiudian	Xiping, Henan	WSP	1	√	
2	Zhenghan Gucheng	Xinzheng, Henan	WSP		√	
3	Gaocheng	Dengfeng, Henan	WSP	1		
4	Qi Gucheng	Linzi, Shandong	WSP to Han		√	
5	Goutouzhao	Wugang, Henan	WSP to Han	3	√	
6	Zhaizhuang	Wugang, Henan	WSP to Han	1	√	
7	Xugou	Wugang, Henan	WSP to Han		√	
8	Yangzhuang	Xiping, Henan	WSP to Han		√	
9	Fuzhuang	Xiping, Henna	WSP to Han			
10	Hancheng	Yiyang, Henan	WSP to Han			
11	Lulou	Hebi, Henan	WSP to Han	13	√	
12	Handan	Handan, Hebei	WSP to Han			
13	Xiangcheng	Huaibei, Anhui	WSP to Han	2		√
14	Dongpingling	Zhangqiu, Shandong	Han	4		√
15	Beiye	Jiaozuo, Henan	Han	2		√
16	Wangfangzhuang	Nanyang, Henan	Han	9	√	
17	Tieshenggou	Gongyi, Henan	Han	8	√	
18	Guxing	Zhengzhou, Henan	Han	2	√	
19	Xiadian	Linru, Henan	Han	1		
20	Wangchenggang	Lushan, Henan	Han	6	√	
21	Ximalou	Lushan, Henan	Han		√	
22	Zhangfan	Tongbai, Henan	Han		√	
23	Xiahewan	Biyang, Henan	Han		√	
24	Xuecheng	Xuecheng, Shandong	Han			
25	Qinghe	Haidian, Beijing	Han			
26	Fengshan	Sihong, Jiangsu	Han	1	√	
27	Tieniucun	Pujiang, Sichuan	Han	1	√	
28	Niya	Mingfeng, Xinjiang	Han			
29	Kuche	Kuche, Xinjiang	Han			
30	Luopu	Luopu, Xinjiang	Han			
31	Pozhui, Liuchen	Pingnan, Guangxi	Han	2	√	
32	Tieshiwei, Dengtang	Pingnan, Guangxi	Han	6	√	
33	Dinglonggang, Dengtang	Pingnan, Guangxi	Han	5	√	
34	Liuxueling, Dengtang	Pingnan, Guangxi	Han	1	√	
35	Jianshuibiao, Dengtang	Pingnan, Guangxi	Han	1	√	
36	Tieshitang, Damiao	Pingnan, Guangxi	Han	1	√	
37	Liuzhuochong, Liuchen	Pingnan, Guangxi	Han			
38	Heshui, Liuchen	Pingnan, Guangxi	Han			
39	Luoxiu	Guiping, Guangxi	Han	7	√	
40	Ershijiazi	Hohehot, Inner Mongolia	Han	16		
41	Liguoyi	Tongshan, Jiangsu	Han	1	√	
42	Yetao	Wuan, Hebei	Han			√
43	Tielugou	Linzhou, Henan	Han to Tang	9	√	
44	Laiwu	Laiwu, Shandong	Han to Tang		√	
45	Gushishan	Pujiang, Sichuan	Han to Song	1	√	
46	Xuxiebian	Pujiang, Sichuan	Han to Tang	1	√	
47	Pinle	Qionglai, Sichuan	Tang to Song	2	√	
48	Fanchang	Fanchang, Anhui	Tang to Song	6		
49	Guishan	Fenyi, Jiangxi	Tang to Ming			
50	Qiyang	Shahe, Hebei	Tang to Song	17		
51	Xiacun	Nanzhao, Henan	Tang to Song	7	√	
52	Jingjicun	Wuan, Hebei	Tang to Song	3		√
53	Cuicun	Wuan, Hebei	Tang to Song			√
54	Shencun	Linzhou, Henan	Song	21	√	
55	Zhuzhuang	Xintai,Hebei	Song	1		
56	Kuangshancun	Wuan, Hebei	Song	1	√	
57	Liuxi, Longan	Xingye, Guangxi	Song	3		
58	Maijiehe	Jiazuo, Henan	Song	1		√
59	Baotou	Baotou, Inner Mogolia	Song	1		√
60	Macun	Wuan, Hebei	Song	1		√
61	Hualu, Tongye	Anyang, Henan	Song to Ming	3	√	
62	Tongan	Tongan, Fujian	Song to Ming			
63	Shangcang	Chicheng, Hebei	Liao		√	
64	Shuiquangou	Yanqing, Beijing	Liao	4		√
65	Lanqiying	Xinlong, Hebei	Liao	2		√
66	Hongshanzhui	Luanping, Hebei	Liao			√
67	Bohaiye	Luanping, Hebei	Liao to Jin	1	√	
68	Acheng	Acheng, Heilongjiang	Jin	7		
69	Washixia	Ruoqiang, Xinjiang	Yuan			
70	Tiechang	Zunhua, Hebei	Ming	2		√

Note: WSP (Warring States Period) (475-221BC); Han Dynasty (202BC-AD220); Tang Dyansty (AD 618- 907); Song Dynasty (AD 960-1279); Liao Dynasty (AD 916-1125); Jin Dyansty (AD 1115-1234); Yuan Dynasty (AD 1271-1368); Ming Dynasty (AD 1368-1644).

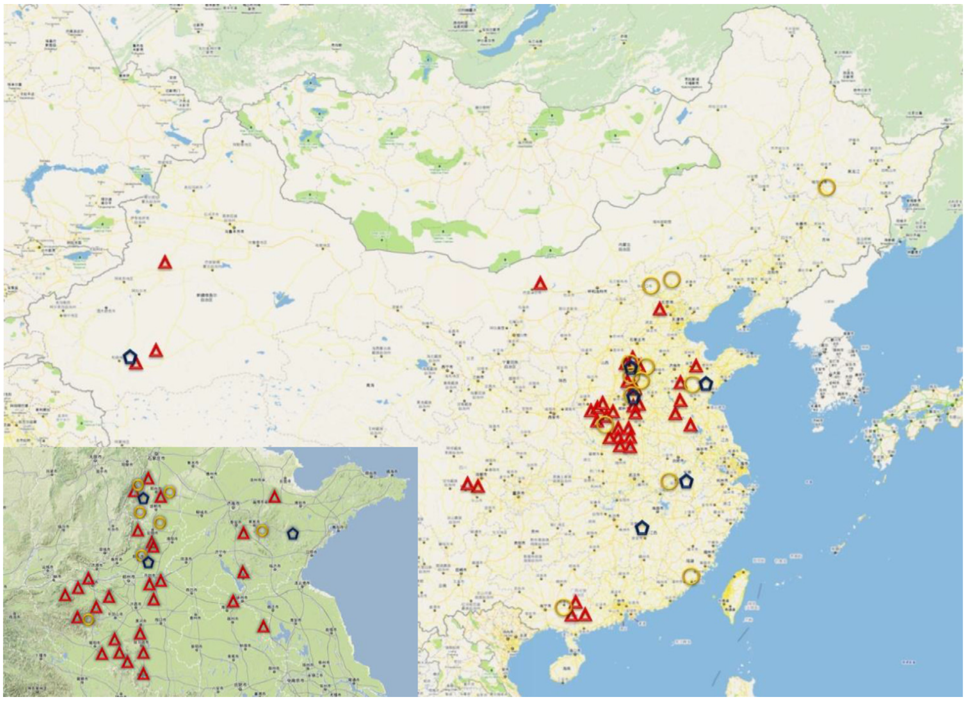

Fig. 2. Chinese iron smelting sites in different dynasties
(475 BC-AD 618, AD 618-1279, AD 1279-1644).

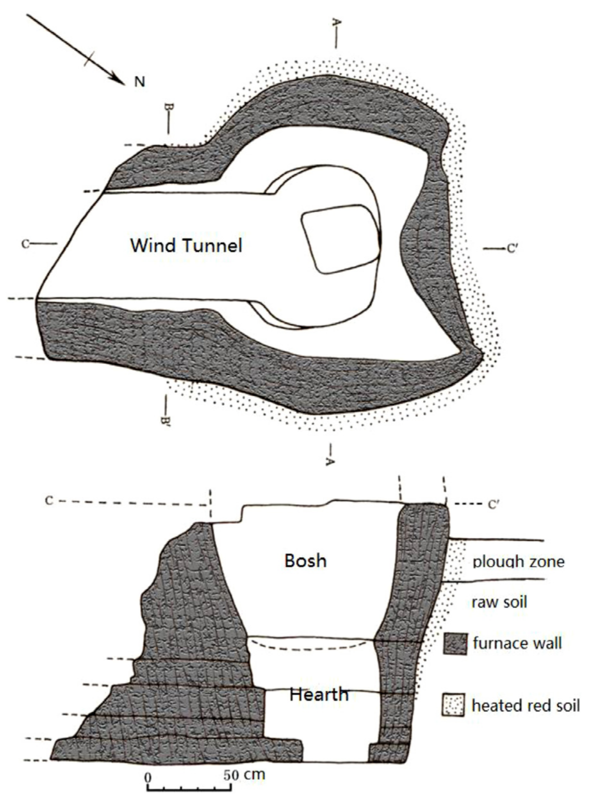

Fig. 3. The plan (top) and section (bottom) of Jiudian furnace (Henan, 1998).

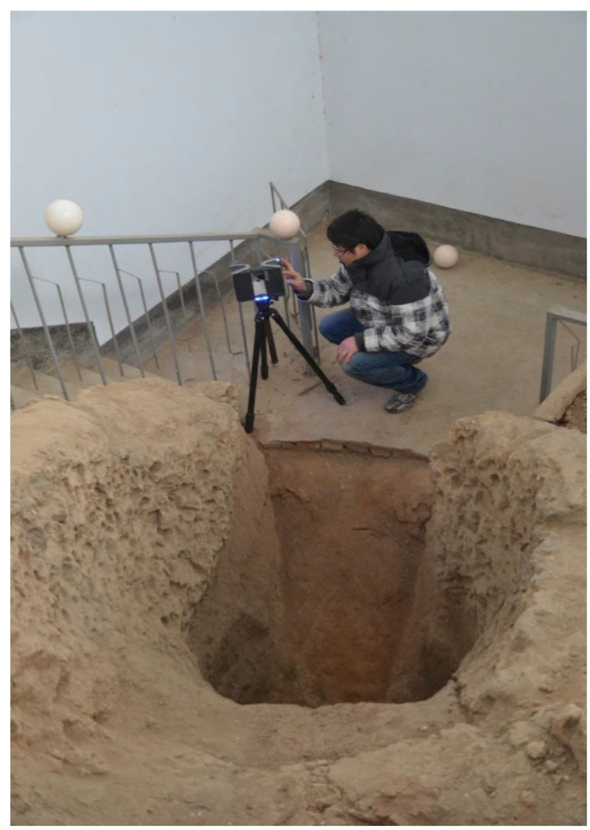

Fig. 4. 3D laser scanning on Jiudian furnace.

by human-powered bellows, assumed the outline and the structure of the furnaces, the construction of flow can be obtained with the software. Furthermore, if the balance of the combustion and chemical reaction in the furnaces were calculated, the temperature distribution could be showed, too. The basic procedure and details of the method can be found in the recent simulation research on the Shuiquangou site (Huang, 2012, 2015).

In this study, we established two kinds of the 3D mesh models of the furnace internal space: bowl and shaft, and a part of the blast tunnel in the software GAMBIT according to the 3D laser scanning (Figure 6

Fig.5. 3D laser scanning result for Jiudian furnace.

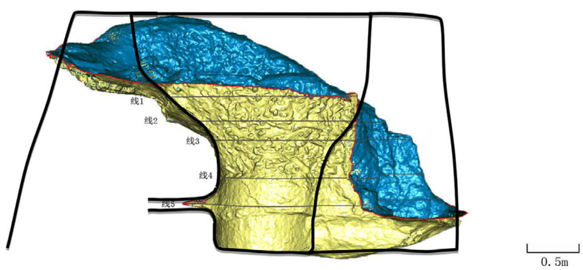

Fig. 6. A reconstruction of the bowl furnace.

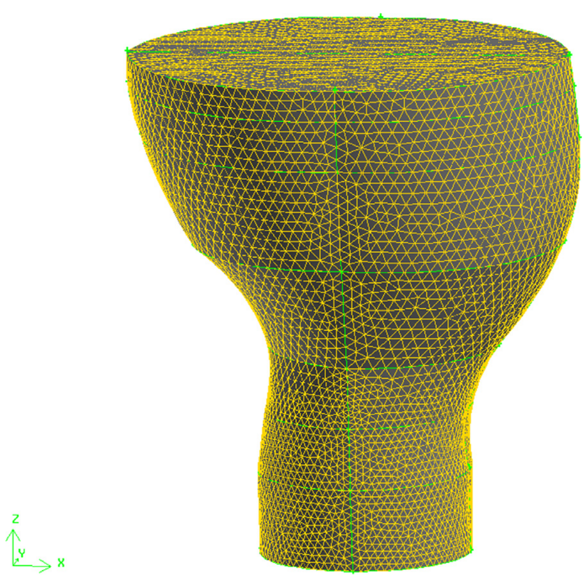

Fig. 7. 3D simulation structure model of bowl furnace.

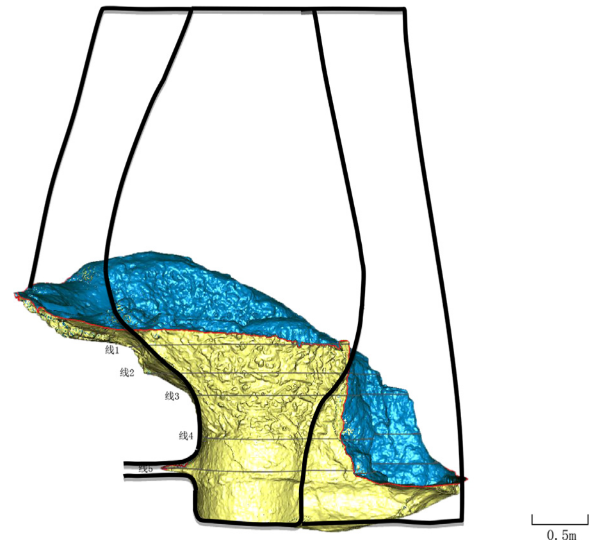

Fig. 8. Reconstruction of shaft furnace.

Fig. 9. 3D Simulation structure model of shaft furnace.

Figure 7 Figure 8Figure 9). Assuming that the furnace was full of the charge of charcoal and ores, a simulation could be done. Before this, a reconstruction of shaft type might be more acceptable. The furnace might be higher with a little hearth angle as well as bosh angle (), according to the other shaft furnaces in later period. The height of the furnace was supposed no more than 4.20 m, for the widest waist was located at about 40–50% of the whole height of furnace, which is the typical short and fat shaft furnace before the 8th century AD (Huang, 2014).

In the Fluent software, the boundary conditions were set as follows. The inner wall surfaces such as the furnace wall, blast tunnel wall and bottom were regarded as wall; blast tunnel inlet was considered as pressure inlet; the furnace top was considered as pressure outlet. The furnace internal space was considered as a porous media.

The blast pressure of the bellows in pre-Qin period could be calculated by taking a skin bellow which was widely used for iron smelting before Tang Dynasty. In a previous study, the blast pressure was calculated using formula (1), and the maximum value could achieve the range from 103 Pa to 104 Pa (Huang, 2013).

$$P = F/S \tag{1}$$

(P: blast pressure, F: thrust power, S: area of skin)

There was an image of skin bellow on the forge iron stone relief unearth at Hongdaoyuan宏道院 in Teng country藤县, Shandong山东 province, in Han dynasty. It was presumed that the men performing the blasting were 1.7 m in height (Fig. 10). So the diameter of skin was 0.5 m, the area was 0.20 m^2, and F was 400 N. Thus, the skin bellow

Fig. 10. A rubbing of the forge iron stone relief unearth at Hongdaoyuan in Han dynasty.

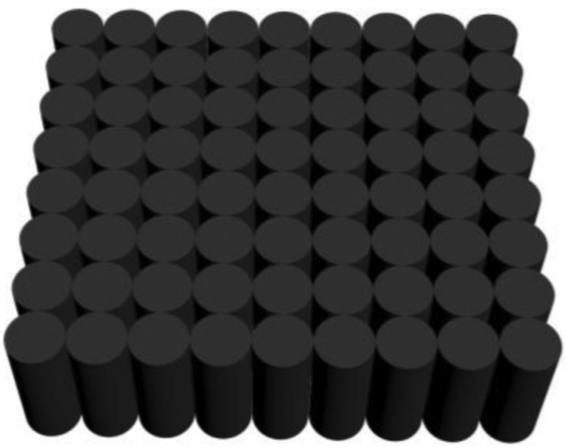

Fig. 11. The charcoal distribution for the low permeability configuration.

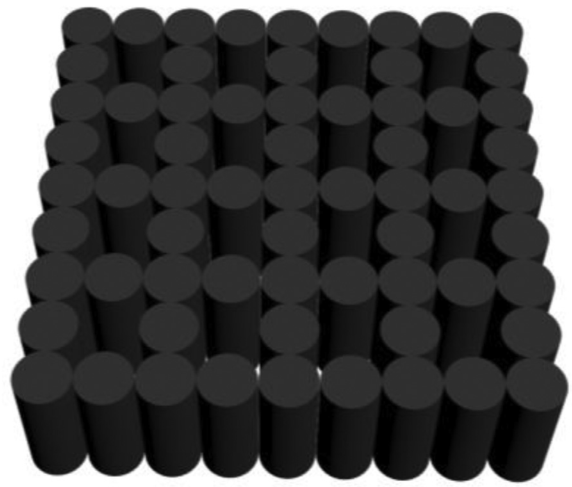

Fig. 12. The charcoal distribution for the high permeability configuration.

could continue to produce a relative blast pressure of approximately 2000 Pa.

FLUENT takes the permeability coefficient 1/a and internal loss coefficient C_2 as the factors of flow permeability (Fluent Inc., 2006). Ergun's equation formula (2) was usually used for the calculation of these factors.

$$\alpha = \frac{D_p^2}{150}\frac{\varepsilon^3}{(1-\varepsilon)^2}; C_2 = \frac{3.5}{D_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{2}$$

(D_p :) average diameter ε : air void

Based on the investigation of similar iron smelting in the 20th century, the volume ratio of the charcoal and the ores-flux was nearly 500:1 (Li, 2003). For simplicity, D_P and ε could be obtained from the charcoal in this study.

In reality, the burden material was piled up randomly. The pores of the burden material were inter-connected, and their shapes and sizes varied. In previous study (Huang, 2015), three burden material accumulation configurations were established to simulate the low, high and median permeability. The first two configurations were extreme cases and do not exist in real smelting conditions. However, the variation range of the flow field can be determined by these configurations. In addition, the most probable situation of the flow field can be determined by the median configuration. The low and high permeability configuration could be calculated by the following geometry model (Figs. 11 and 12).

Because the cross section of the open space between the charcoal pore was not a circle, the D_p can be seen as the hydrodynamic diameter (d_h) and calculated according to the minimum size of the charcoal diameter as formula (3). And the marks on the furnace wall shows that the charcoal is 4 cm in diameter(Figure Fig.13).

$$d_{h\ min} = \frac{4s}{C} = \frac{(4-\pi)d}{\pi} \approx 0.011 \text{ m} \tag{3}$$

$$d_{h\ max} = \frac{4s}{C} = \left(\frac{16}{3\pi} - 1\right)d \approx 0.042 \text{ m}$$

(s: cross section area of the pore C:pore section perimeter)

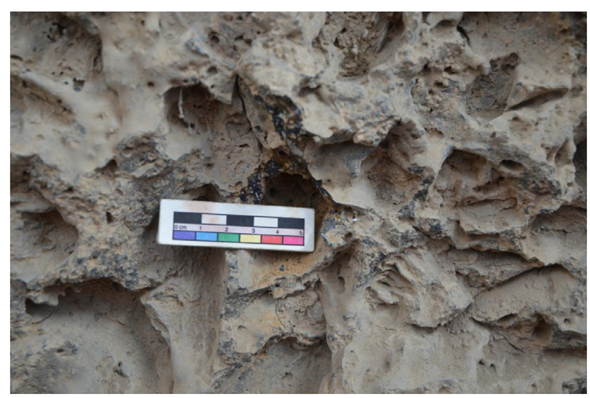

Fig.13. the marks on the furnace wall for Jiudian furnace.

The air void (ε) can be calculated as follows. The calculation at the fringing field can be dismissed. For the internal area, the percentage of the air void was equal to the ratio of the circle and its circumscribed cuboid, as formula (4):

$$\varepsilon_{min} = \frac{S_h - S_c}{S_h} \approx 0.215 \tag{4}$$

$$\varepsilon_{max} = 411$$

Because the charcoal was piled up randomly. The median values (arithmetic mean) of $\boldsymbol{D_P}$ and $\boldsymbol{\varepsilon}$ were chosen to represent the probable conditions in reality.

$$\boldsymbol{d_{h\ \mathrm{med}}} = 0.027,\ \boldsymbol{\varepsilon_{\mathrm{med}}} = 0.313$$

As result:

$1/a=3.166 \times 10^{6,}$ $C_2=2.904 \times 10^3$

In addition to the above calculations, standard k-ε model was used to calculate the turbulent viscosity, and the standard SIMPLE algorithm

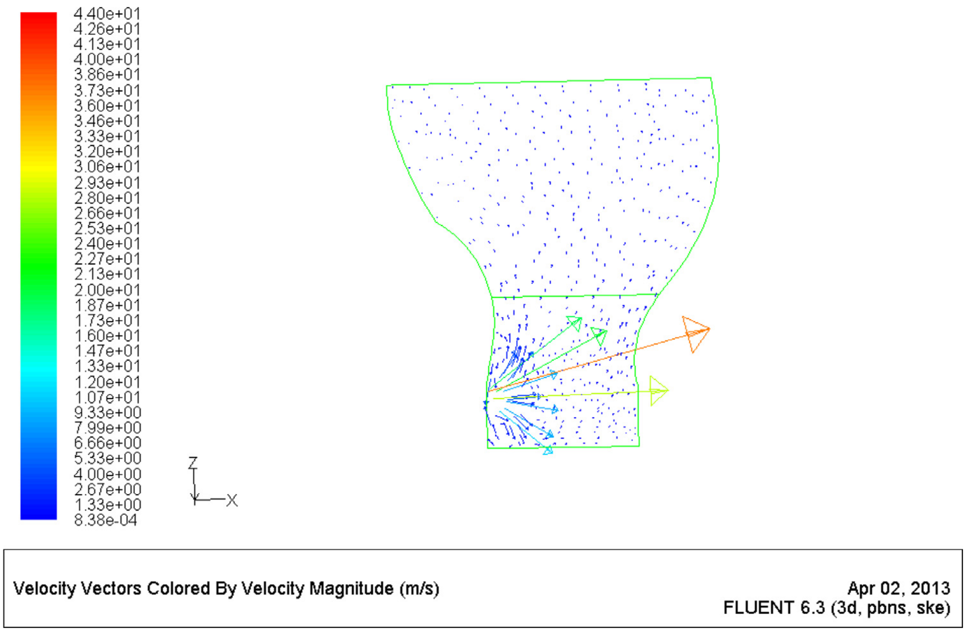

Fig. 14. Fluid distribution in the full charge bowl furnace.

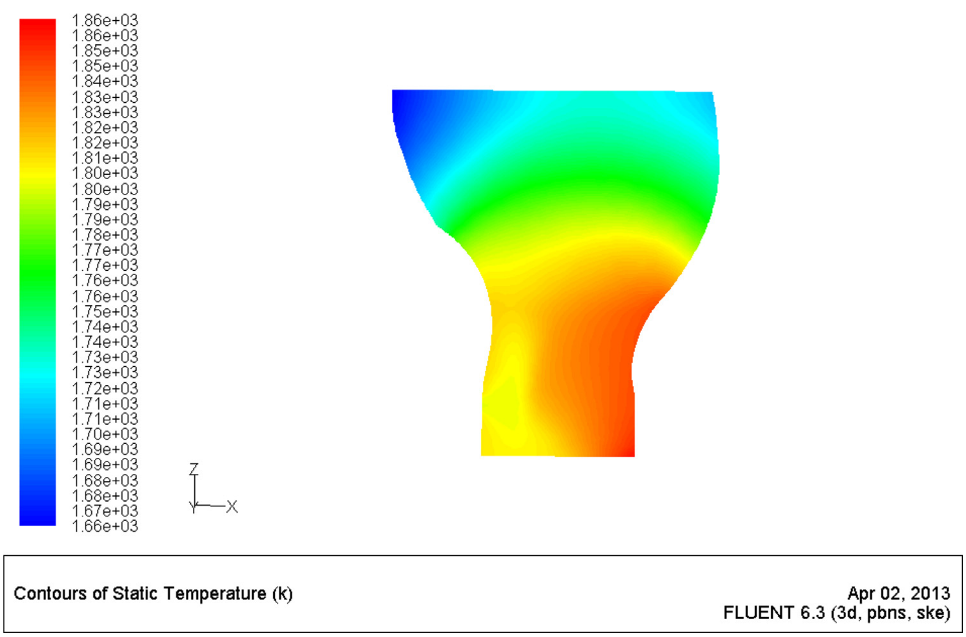

Fig. 15. Temperature distribution of the bowl furnace.

was used in the pressure-velocity coupling k-ε. It was shown by the residual plots that convergence results were obtained from the simulations. For simplicity, only the residual plots of key results are shown.

The flow field is heavily influenced by temperatures. In the furnace, the temperature distribution is uneven. According to the ferrous metallurgy theory, for the ancient furnace, the temperature is around 1800 K near the tuyère, dropping to around 700 K near the furnace top; and the temperature in the central region is higher than it in the outer region. In this simulation, in order to make the simulation result of the flow field more convincing, the energy equation and a comparing method about the heat was adopted, by artificial setting of the total temperature of inlet flow, the number of energy sources of the inner space, and heat flux of furnace wall (heat loss). After repeated optimization simulation, the results of the temperature field were basically consistent with facts. And the distribution of fluid velocity could be measured along with the temperature distribution.

In these conditions, the fluid distribution (Fig. 14) and temperature distribution (Fig. 15) of the blow furnace was simulated with the software Fluent, and got a convergent result. It indicated that the blast was only concentrated near the tuyère and it was difficult to blow into other parts of the furnace. Therefore, the temperatures were seriously inhomogeneous in the different parts of hearth and bosh.

In the same conditions, the fluid distribution (Fig. 16) and temperature distribution (Fig. 17) of the shaft furnace was simulated with the software Fluent, and got a convergent result too. It indicated that the blast was not only concentrated near the tuyère and would flow to the other parts of the furnace as a similar velocity, therefore the temperatures were even and well distributed in different parts of base, hearth and bosh.

The comparative simulation showed the same trend that there might be a higher temperature in the front wall on the other side to the tuyère than other parts of the wall, which could explain why the front wall could be destroyed at the first when the life of the furnace was in their deadline. The well-distributed fluid and temperature showed the shaft furnace might be used instead of the bowl one. Although the details of the furnace wall were not clear in the archaeological excavation, the

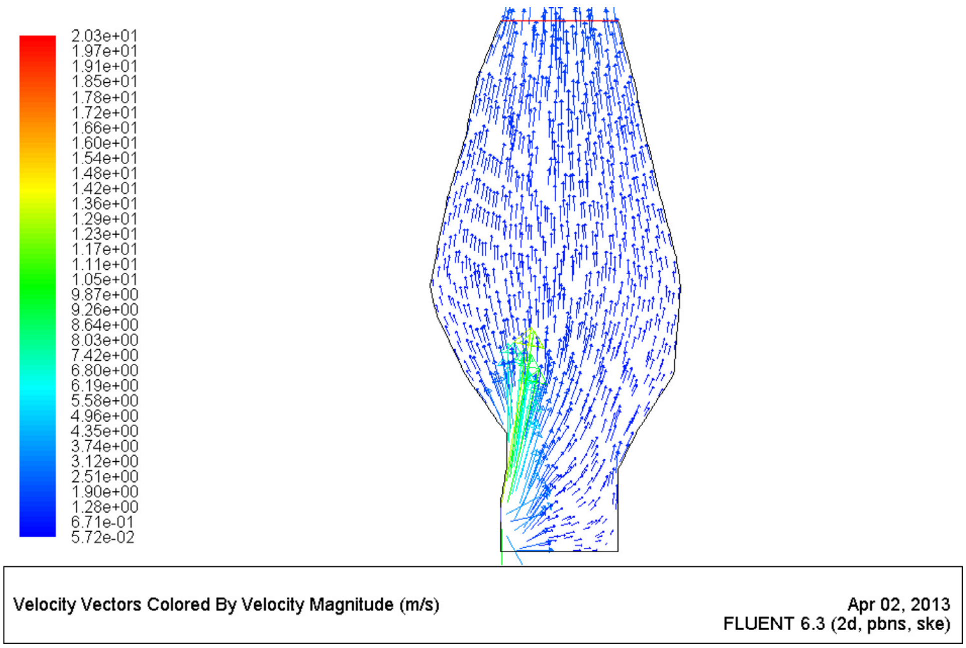

Fig. 16. Fluid distribution in full charge shaft furnace.

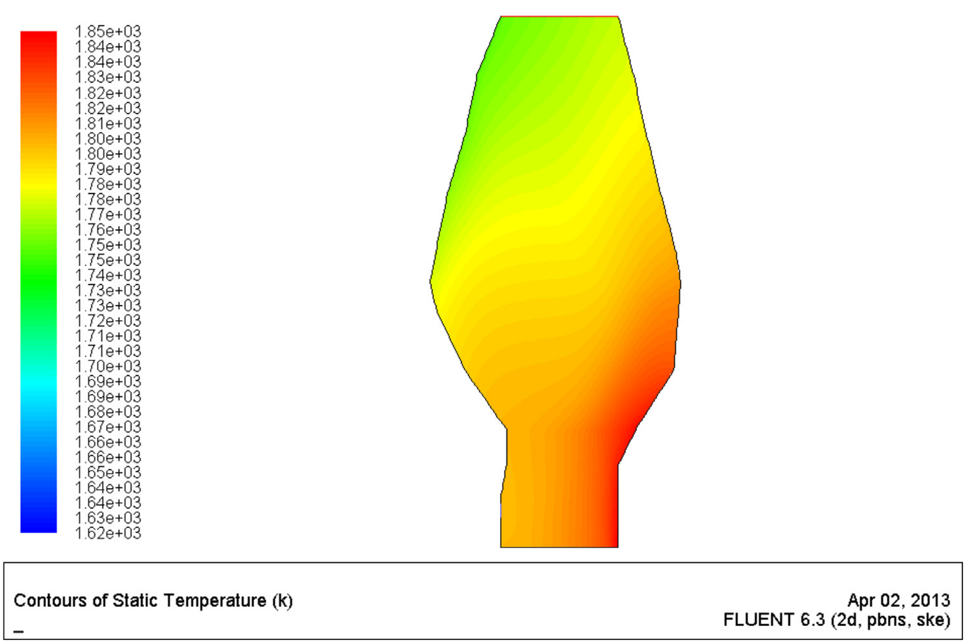

Fig. 17. Temperature distribution of bowl furnace.

simulation could help reconstruct an acceptable outline of the furnace. So far, the Jiudian furnace might be the earliest blast furnace with the shaft and tuyère unearthed in China.

Discussion

Although many smelting sites have been investigated throughout China, the evidence for the evolution of the iron smelting furnaces is still insufficiently clear. There is still a major question to find how and why cast iron was invented and developed in China.

The chemical reaction in the furnace includes the direct and indirect ones with very complicated physical and chemical processes. The reaction was too complicated to computerise, so these numerical simulations were mainly on the velocity and temperature on the basis of theoretical models. This would lead the simulated result deviating to the correct points. Further work should be done by collecting more information of the process such as the boundary conditions etc. For instance, the firing temperature of the refractory and slag could be useful to compute the inner wall temperature in the models. In this case, for the iron smelting process in the furnace was roughly an endothermal reaction, the simulated temperature might be a little higher than the real one. The tendency of the fluid and temperature distributions could obviously help to distinguish which model was more acceptable.

A comparative simulation study could give us a clear understanding of the thermal efficiency of different reactors and how a shaft furnace with a little hearth and bosh angles showed better thermal efficiency than a bowl furnace. That means the iron could be melted into liquid cast iron at a higher temperature in this kind of shaft furnace - comparable to a modern blast furnace. This was difficult to obtain in the bloomery furnace just like the bowl type. This might be one of the key technical reasons why cast iron was invented in China.

In the case of Jiudian furnace, 3D laser scanning played a very important role in the new find of the blowing hole. It was so effective a new technology that it was widely used in archaeology and conservation work to collect large amount of information in a short time, which was especially helpful in fieldwork. Though the data treatment for the scanning was not easy, it might be an efficient method to measure the inner size of containers or tunnels with complicated shapes such as mines, kilns and furnaces, which were the main reactors of pyrotechnology.

Besides the social demands, the technical reasons might be also considered as good explanations for the puzzle of cast iron invention. As a major pyro-technology, cast iron technology shows an obvious relationship with other pyro-technologies such as the manufacture of bloomery iron, ceramics, copper and bronze. How to control the fire and get high temperatures efficiently was the main objective for the inventors and innovators. This can be analysed through the techniques of furnace building which are underpinned by furnace styles and refractory materials. A furnace was a better reactor than crucible and kiln due to its inner-burning system and blast blowing. Almost at the same period when cast iron was invented, porcelain was invented on the basis of glazed pottery, while glassmaking was developed in relation to copper metallurgical slag according to the result of the examination and analysis of the glass beads unearthed from Kizilur克孜尔 Cemetery of Baicheng拜城 County in Xinjiang Region (Qian, 2010). It might not be occasional that such pryro-technologies were invented and developed almost at the same period. The secret of the pyro-technology is the high temperature with combustion in a good shape chamber and excellent air blowing. Techniques were borrowed not only from other pyro-technologies, but also from other states and communities. Cast iron was invented when the introduced bloomery iron smelting from the west met the local advanced bronze foundry and copper smelting furnace.

The history of cast iron informs us that the technology development might happen in an open social context so that the technical knowledge could be produced and transmitted widely. The cast iron smelting invention is an example of high harmonious and systemic technical thought in ancient China. The inherent culture of Chinese technology of *he*和 (harmonious) led the special way to develop cast iron technology which was quite different to the West. It can be argued that the invention of cast iron is one consequence of a distinct philosophical approach to technology that started in the Western Zhou Dynasty (1046-771BC) and was fully developed in the Eastern Zhou Dynasty (770-256BC), when a variety of philosophers such as Confucius flourished. The technical thought was so different from that of the West that they developed two opposite systems of iron smelting and making methods: casting, decarburising and annealing in China; bloomery, carburising and forging in the West. The philosophical approach focussed on the inter-relationships of system over its structural analysis and the details of the component parts. A potential analogy can be seen in the contemporary inventions of cast iron smelting and medical techniques in China. The operators could decide the exact treatment through the changes of flash and slag, just like the doctors could do through the facial changes in the human body. They all believed the inner relations in one system, and paid more attention to the relations instead of the structure analysis and part details.

Cast iron and its steel products replaced copper and bronze as the most important materials to manufacture the farm implements. By the late 4th to 3rd century BC, permanent moulds for casting iron items had been developed, greatly increasing productivity, the precision of casting and the capacity to replicate objects such as ploughshare tips. This can be considered a primitive model of mass production and standardisation. Standard moulds for casting were issued by the iron officials of the Han dynasty to different foundries. The weapon material was replaced by the iron and steel a short time later than the implements. These two innovations of tools and weapons enlarged the population of China rapidly in the second half of the first millennium BC, which promoted the formation of a unified Chinese Empire.

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