Master Thesis Assignment: Mathematical Modeling and Numerical Simulation of Non-Premixed Turbulent Combustion and Pollutant Formation in a Hot Blast Stove

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1 Introduction

Danieli-Corus (see danieli-corus.com) is an international company that designs, installs and services steel manufacturing plants. Its offices in Ijmuiden (north of Amsterdam) is currently looking into the design of new gaseous fuel burners in hot blast stoves to cut back on the formation of pollutants such as nitric-oxides and carbon monoxide.

2 Mathematical Modeling and Numerical Simulation

Steel is produced in blast furnaces. The process requires hot air. This air is supplied by the hot air or blast stove. The function of the hot blast stove is thus to preheat large amounts of air.

In the hot blast stove, heat in produced by the combustion of natural gas (mainly methane) as fuel. The flame heats the lateral surfaces of the large cylindrical enclosures shown in Figure 1. Heat is forced to flow along these lateral surfaces and is thus heated.

In a previous stage of the collaboration with Danieli-Corus, master students of the TU Delft developed a computational fluid dynamics model for the turbulent iso-thermal non-reactive flow in the hot blast stove. This model needs to be extended with a model for the chemical reactions of the combustion of the gaseous fuel, a model for the radiative heat transfer in the furnaces and a model for the formation of the pollutant. The outcome of the model ought to be validated in the field. Various configurations for the gaseous fuel burner and the furnace can be compared.

Figure 1: Hot blast stove supplying hot air in the steel making process.

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Dome Combustion Hot Blast Stove for Huge Blast Furnace

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Abstract: In Shougang Jingtang 5 500 m^3 huge blast furnace (BF) design, dome combustion hot blast stove (DCHBS) technology is developed. DCHBS process is optimized and integrated, and reasonable hot blast stove (HBS) technical parameters are determined. Mathematic model is established and adopted by computational fluid dynamics (CFD). The transmission theory is studied for hot blast stove combustion and gas flow, and distribution results of HBS velocity field, CO density field and temperature field are achieved. Physical test model and hot trail unit are established, and the numeral calculation result is verified through test and investigation. 3-D simulation design is adopted. HBS process flow and process layout are optimized and designed. Combustion air two-stage high temperature preheating technology is designed and developed. Two sets of small size DCHBSs are adopted to preheat the combustion air to 520—600 ℃. With the precondition of BF gas combustion, the hot blast stove dome temperature can exceed 1 420 ℃. According to DCHBS technical features, reasonable refractory structure is designed. Effective technical measures are adopted to prevent hot blast stove shell intercrystalline stress corrosion. Hot blast stove hot pipe and lining system are optimized and designed. After blowing in, the blast temperature keeps increasing, and the monthly average blast temperature reaches 1 300 ℃ when burning single BF gas.
Key words: dome combustion hot blast stove; high blast temperature; ceramic burner; high temperature combustion air preheating; CFD

Hot blast temperature is the important technical feature and development orientation of modern blast furnace (BF) iron making. Increasing blast temperature can reduce fuel consumption and improve blast furnace energy utilization efficiency effectively. If the blast temperature can be increased by 100 ℃, the coke rate can be saved by 15 — 20 kg/t, and beneficial conditions can be exerted on pulverized coal injection (PCI).

In Shougang Jingtang 5 500 m^3 BF design, three kinds of hot blast stove (HBS) technologies including internal HBS, external HBS and dome combustion hot blast stove (DCHBS) are studied and analyzed. On the basis of Shougang DCHBS technology[1] and Russia Kalugin DCHBS[2], the advantages of two kinds of technology are integrated, and Beijing Shougang Kalugin (BSK) new DCHBS technology is developed and designed. It is the first time to apply DCHBS in 5 000 m^3 grade huge BF worldwide[3].

1 Dome Combustion Hot Blast Stove

1.1 Optimized integration of technical process for DCHBS

In the design of Shougang Jingtang 5 500 m^3 BF, the technological equipment and operation conditions of existing 13 sets of huge BF above 5 000 m^3 worldwide are studied and analyzed. The 4 000 m^3 grade large BF worldwide mainly uses external HBS, with several exceptions which use internal HBS. The 5 000 m^3 grade huge BFs all use external HBS. There is no previous application of DCHBS on BFs above 4 000 m^3 worldwide.

Through modern research methods including HBS combustion, gas and air flow and heat transmission theory, computational fluid dynamics (CFD) simulation, physical model flow field analysis, pilot trial of cold phase and hot phase, etc, a series of design and study is carried out on HBS, and BSK-DCHBS technology suitable for huge BF is designed and developed.

BSK-DCHBS combines the technical advantages of Shougang type and Kalugin type DCHBS. The main technical features are as follows. 1) The circular ceramic burner of DCHBS is arranged at dome position which has wide operating condition adaptation, can fulfill the multi-operating conditions of gas

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and combustion air with large combustion power, high combustion efficiency and long service life. Circular ceramic burner uses cyclone pervasion combustion technology, which can ensure the complete mixing and combustion of combustion air and gas and increase the flame temperature and dome temperature. 2) Dome space is used as combustion chamber, independent combustion chamber is deleted, and heat stability of stove proper is improved. Ceramic burner is arranged at dome position. High temperature fume is distributed evenly under cyclone condition. The evenness and heat transmission efficiency of high temperature fume on regenerative chamber checker brick surface can be effectively increased. 3) Regenerative chamber uses high efficiency checker brick. Checker brick channel diameter is relatively decreased, and the heating surface of checker brick is increased. Thus, hot blast stove heat transmission efficiency is improved. 4) HBS fume waste heat is reused to preheat the gas and combustion air. The combustion air is preheated above 520 ℃ by preheating stove. The blast temperature can reach 1 300 ℃ using BF gas only. 5) HBS high temperature and high pressure pipe system adopts low stress design philosophy. By means of pipe system and refractory material structure optimized design, stable transferring of 1 300 ℃ high temperature hot blast can be achieved[4].

1.2 Determination of numbers for DCHBS

Most of 5 000 m^3 grade huge BFs worldwide adopt 4 HBSs to improve the dependability of HBS system stable operation. Approved by oversea operation practice, blast temperature can be increased by 30 ℃ when 4 HBSs are operated under staggering parallel operating condition[5]. Considering the worldwide 5 000 m^3 huge BF HBS operation practice, in order to achieve long service life, high efficiency and stable operation of BF, Shougang Jingtang 5 500 m^3 BF is configured with 4 DCHBSs, adopting "two burning, two blasting" staggering parallel burning-blasting process. According to different HBS operation modes, reasonable HBS operating period is designated which can reduce the HBS heat accumulation. High blast temperature of 1 300 ℃ can be achieved using BF gas only. When 4 stoves are under staggering parallel blasting, HBS burning time is 60 min, blasting time is 48 min and change-over time is 12 min.

1.3 Technical specifications

The designed blast temperature of Shougang Jingtang 5 500 m^3 BF-BSK DCHBS is 1 300 ℃ (maximum temperature is 1 310 ℃), dome temperature is 1 420 ℃ (maximum temperature is 1 450 ℃), and the design campaign life is above 25 years. The HBS fuel is BF gas only. HBS fume waste heat recovery unit is used to preheat the gas and combustion air. Two sets of small size stoves are provided to preheat combustion air, which can be preheated above 520 ℃. The HBS high temperature valves are cooled by demineralized water closed circulating cooling system. The HBS system burning, blasting and change-over can be controlled full-automatically. Staggering parallel burning-blasting mode is adopted, and blast temperature of 1 300 ℃ can be achieved using BF gas as fuel only. The blast temperature can reach 1 250 ℃ when using other burning-blasting modes[6]. Table 1 shows

Table 1 Main technical specifications of BSK-DCHBS

Item	Parameter
HBS number	4
HBS height/m	49.22
HBS diameter/m	12.50
Regenerative chamber section area/m^2	93.21
Checker brick height/m	21.48
Checker brick channel diameter/mm	30
Designed blast temperature/℃	1 300 (maximum of 1 310)
Dome temperature/℃	1 420 (checker brick top maximum temperature is 1 450)
Fume temperature/℃	Average 368, maximum 450
Combustion air preheating temperature/℃	520—600
Gas preheating temperature/℃	215
Blast flow volume/($m^3 \cdot min^{-1}$)	9 300
Blast time/min	60
Burning time/min	48
Change-over time/min	12
Checker brick heating area/($m^2 \cdot m^{-3}$)	48
Heating area of each stove/m^2	95 885
Unit BF volume checker area/($m^2 \cdot m^{-3}$)	69.73
Unit blast flow volume checker area/($m^2 \cdot m^{-3} \cdot min$)	41.24

the main technical specifications of BSK-DCHBS.

2 Transfer Theory of DCHBS

2.1 Combustion feature of CFD

Based on hydrodynamics mass conservation, momentum conservation and energy conservation theory, governing equations are built, and original conditions and boundary conditions are set. Numerical calculation is carried out through CFD numerical model on BSK-DCHBS. Transmission theory of BSK-DCHBS burning process is studied. Distribution of velocity flow field, concentration field and temperature field inside combustion chamber of BSK-DCHBS is analyzed. The design structure of HBS and burner is optimized according to study result and the distribution of HBS high temperature fume inside combustion chamber is more even. Fig. 1 to Fig. 4 are the simulation calculation results of velocity field, flow curve field, CO concentration field and temperature field inside combustion chamber of BSK-DCHBS[7].

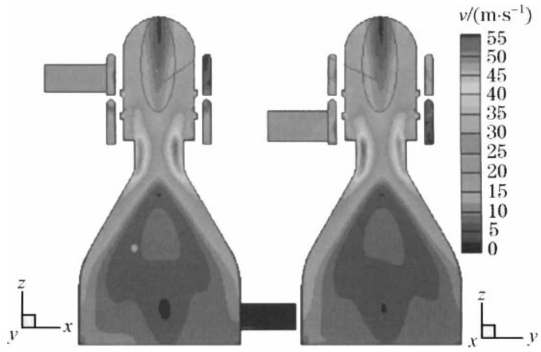

Fig. 1 Flow velocity field distribution of DCHBS

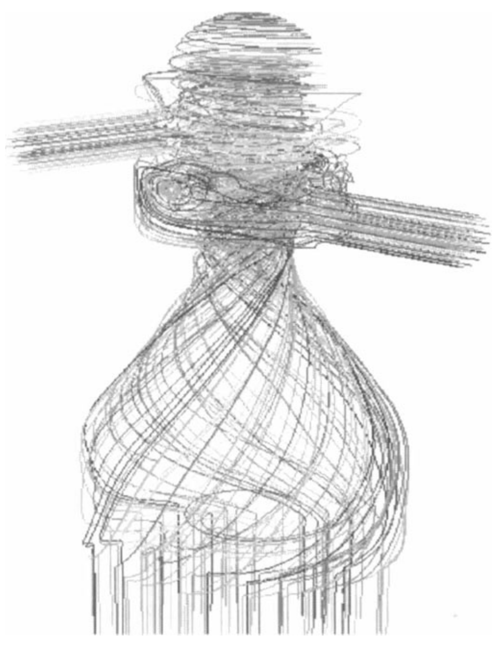

Fig. 2 Flow curve distribution of DCHBS

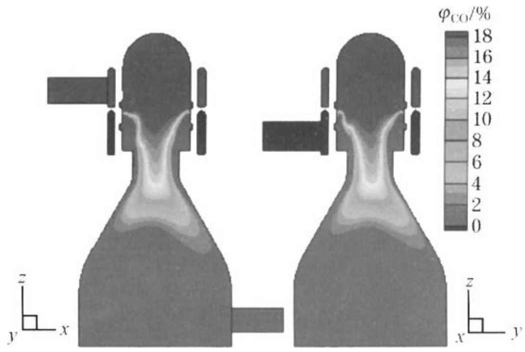

Fig. 3 CO concentration field distribution of DCHBS

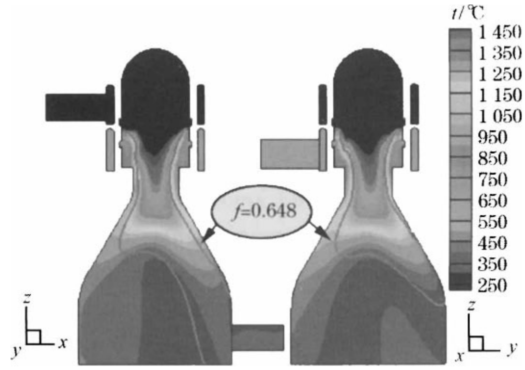

Fig. 4 Temperature field distribution of DCHBS

2.2 Physical model test

In order to verify the correctness of numerical calculation result, according to original design model parameters, original conditions and boundary conditions of numerical calculation, plexiglass physical model of HBS burner is built following similarity principle, and physical simulation test unit of high efficiency cyclone pervasion DCHBS is built in 1 : 10 scale of geometry size. Through physical model test study, the following targets can be achieved: 1) The velocity, pressure and temperature, etc of physical model test unit can be measured and compared with CFD numerical calculation result in order to verify the correctness of numerical calculation results. 2) According to similarity principle, normal temperature air is used to simulate BF gas, and heated air is used to simulate combustion air. The flow field of physical model is put into second simulation zone by adjusting the flow rate of combustion air and gas. Euler dimensionless number is basically unchanged. Actual pressure loss of BSK HBS is measured according to measured pressure loss in order to compare and verify the flow field numerical calculation result. 3) Through measuring the gas flow rate at different injection positions of circular burner, the evenness of gas distribution is verified. 4) By adjusting the structure type and angle of combustion air and gas nozzle, the gas flow rate is evenly distributed; actual ceramic burner of HBS design is optimized. The numerical calculation results are verified by physical model simulation test.

2.3 Hot state simulation trial

The HBS hot state simulation test is to investigate in more details the transmission theory of DCHBS combustion, fluid dynamics and heat transmission. Two hot trial stoves are built for Shougang Jingtang 5 500 m^3 BF HBS in 1 : 10 scale, and "one stove burning-one stove blasting" mode is adopted to simulate the actual working conditions of HBS.

At two hot trial stoves, 289 temperature measuring points and corresponding gas flow measuring points are equipped, and several HBS hot trials are carried out. By online monitoring the regenerative chamber checker brick temperature change under burning condition and blasting condition in trial HBS, considering the pressure measuring and fume element measuring, temperature field distribution and burning condition inside trial stove can be analyzed. The HBS hot trial can verify directly the numerical calculation results of DCHBS burning and heat transmission process, and can provide theoretical and test basis for actual HBS optimized design and reasonable checker brick configuration.

3 Research and Design

3.1 3-D simulating design

In the design, HBS process arrangement is studied, and new rectangular process arrangement is designed and developed considering existing Shougang rectangular layout. The new HBS rectangular process layout has compact process layout, smooth and short flow process, reducing the hot blast main length significantly. 4 stoves are arranged in non-symmetrical rectangular type, and hot blast vertical pipe is arranged outside the rectangular area of 4 stoves. Independent HBS frame is arranged to support pipe and valves. One bridge crane can fulfill all the equipments maintenance requirement in HBS area.

As DCHBS burner is arranged at dome position, the installation positions of all pipes and valves are relatively higher. Influenced by the HBS heat expansion, the pipe system stress and heat expansion shifting are more complicated, and the requirement on pipeline system design and stress calculation is more accurate. Especially for the pipeline system design in HBS area, reasonable pipe stress, easy installation, operation and maintenance shall be considered generally. In order to improve design accuracy and arrange pipe reasonably, 3-D computer aid optimized design is adopted, and compact arrangement and reasonable flow of HBS is achieved. Fig. 5 is the 3-D simulation design of DCHBS for No. 1 BF at Shougang Jingtang.

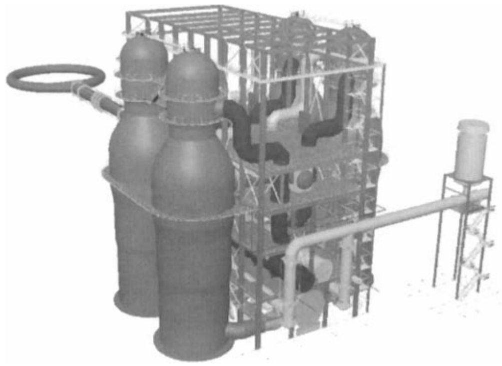

Fig. 5 3-D simulating design of DCHBS for No. 1 BF at Shougang Jingtang

3.2 Combustion air high temperature preheating technology

In order to achieve 1 300 ℃ blasting temperature with only BF gas, general technical measures are studied to increase HBS flame temperature and dome temperature. On the basis of combustion air high temperature preheating technology developed by Shougang[8], high efficiency long service life gas and combustion air two-stage preheating technology is designed and developed[9].

Its main technical theory is as follows: separated type hot tube heat exchanger is used to recover the HBS fume waste heat and preheat the gas and combustion air. The temperature of gas and combustion air can reach about 200 ℃ after preheating. This cycle is called No. 1 stage double preheating. Two sets of small size stoves for combustion air high temperature preheating are used to preheat the combustion air to above 520 ℃. The gas and combustion air used in combustion air preheating stoves are from hot tube heat exchanger No. 1 stage preheating. Two preheating stoves can be operated alternatively in order to preheat some combustion air used for HBS burning. The combustion air temperature can reach 1 200 ℃ after preheating which is mixed with combustion air from No. 1 stage preheating. The mixed combustion air temperature is controlled at 520—600 ℃. This process is called No. 2 stage preheating. This process is a self-recycling preheating process. The physical heat of combustion air and gas can be increased significantly. The HBS dome temperature can be increased to 1 420 ℃ or abover. The blast temperature can be increased effectively, and general heat utilization of HBS can be improved remarkably. Fig. 6 is the combustion air and gas preheating system process flow scheme.

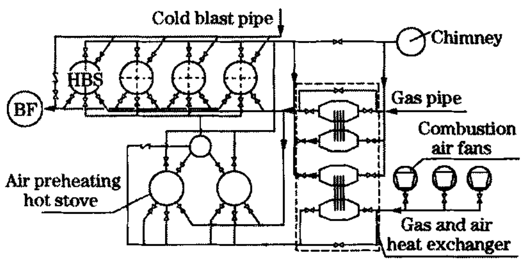

Fig. 6 Process flow sheet of preheating for combustion air and gas

3.3 Circular ceramic burner

In order to fully utilize the dome space, completely burn the gas and distribute evenly the high temperature fume in regenerative chamber, cyclone pervasion combustion technology is adopted. The nozzles of circular ceramic burner gas and combustion air are arranged along tangent to periphery. Two rings of gas nozzles are arranged at the burner top with downward inclination, and two rings of combustion air nozzles are arranged at burner bottom with upward inclination. The injected flow can be mixed inside pre-mixing chamber with certain velocity and revolve downwards, intensify the pervasion mixing of gas and combustion air, in order to achieve complete combustion of gas. In order to achieve the even distribution of gas, reasonable circular ceramic burner pre-mixing chamber and cone dome geometry structure is designed. Through fume flow shrinking, expansion, cyclone and return flow in dome space, the gas can be burned completely and high temperature fume can be distributed evenly. Fig. 7 is the circular ceramic burning design structure.

BSK-DCHBS circular ceramic burner is completely suitable with the combustion condition of preheating combustion air to 600 ℃ and preheating gas to 200 ℃. The burner adopts cyclone pervasion burning type and has big regulation range of combustion air and gas flow rate, complete and even mixing. Before high temperature fume enters regenerative chamber checker brick, the combustion is complete, which can restrain effectively the section high temperature zone in dome and reduce NO_x emission. After burning,

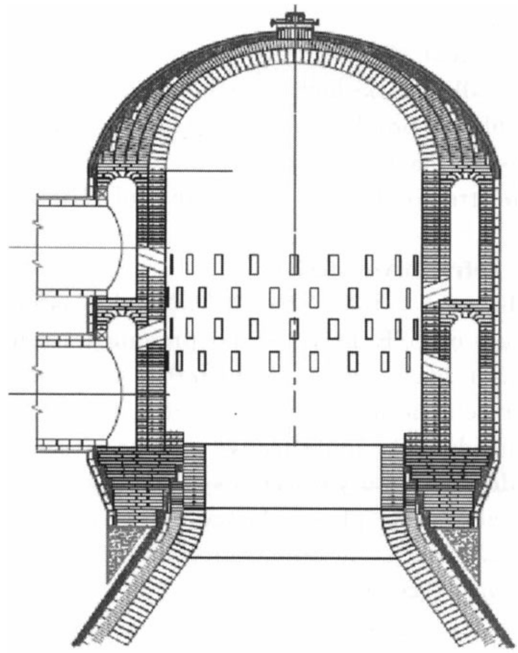

Fig. 7 Design construction of circular ceramic burner for BSK-DCHBS

the high temperature fume flow field is distributed evenly and properly. The results of CFD numerical calculation and physical model simulation test verify that flow field inside HBS can fulfill the design requirement.

3.4 Intercrystalline stress corrosion prevention

Intercrystalline stress corrosion exists widely in high blast temperature HBS. The main reason is that when HBS dome temperature exceeds 1 400 ℃, the formation of NO_x increases quickly and its concentration reaches 350×10^{-6} or above. NO_x combines with the condensed water at HBS inner wall and forms corrosive acid. The corrosive acid penetrates deeply, expands and cracks along the crystal lattice from shell position with stress. The pulse pressure and tiredness stress during HBS operation enhance corrosion and cracking process. The HBS high temperature area shell intercrystalline stress cession becomes the restriction condition of influencing HBS campaign life and improving blast temperature.

In BSK-DCHBS design, the maximum design temperature of HBS dome is controlled within 1 450 ℃, and normal operating temperature is controlled within 1 420 ℃ in order to ensure safe temperature operation of HBS, control NO_x formation and prevent intercrystalline stress corrosion effectively. Also low alloy microlite corrosion proof steel plate is adopted. Welding stress generated during shell manufacturing is eliminated. Corrosion proof painting is applied at inner wall of HBS high temperature area shell. One layer of acid proof gunning material is used at corrosion proof painting in order to increase the intercrystalline stress corrosion proof ability of HBS shell.

3.5 Refractory material

In order to fulfill the 1300 ℃ high blasting temperature of BSK DCHBS and prolong its campaign life, hot blast refractory material and bricklaying structure is designed and optimized. Low stress design is adopted, and effective measures to eliminate or reduce refractory material system heat stress, mechanical stress, phase change stress and pressure stress are used. According to working conditions of different HBS areas, different refractory materials are used to achieve the optimized selection of HBS refractory material. In HBS high temperature area, silicon bricks with high temperature proof and good creep performance are used. In middle temperature zone, andalusite bricks and low creep clay bricks are used. In low temperature zone, high density clay bricks are used. The optimized configuration of refractory material adapts with the working characters of DCHBS, improves the economic rationality of refractory material and reduces the project investment.

Low creep mullite bricks and insulation bricks composite bricklaying structure is adopted for hot blast main, hot blast branch and hot blast bustle. Two layers of indefinite form refractory material are used at internal surface of pipe shell. One layer of ceramic fiber felt is filled between pipe upper bricks and gunning material. The expansion joints at hot blast pipe bricklaying are filled with ceramic fiber material which can resist 1420 ℃ high temperature and absorb the heat expansion of refractory material lining stably. In order to prolong the service life of hot blast main and branch, one layer of acid proof painting to prevent intercrystalline stress corrosion is applied at internal wall of hot blast pipe shell.

As working under several bad operational conditions, all holes and openings of HBS are the weak points for HBS long life and blast temperature improving. In order to prolong the service life of HBS holes and openings, composite brick structure is applied at hot blast outlet, T-section of hot blast pipe, gas inlet and combustion air inlet, etc. The hot blast outlet is composed of independent ring type composite brick. Among composite bricks, biconcave tenon groove structure is used for intensifying. Above composite bricks, semi-ring special arch bricks are used to reduce the pressure stress generated by upper stove wall brick lining on composite bricks.

3.6 Hot blast pipe

The hot blast branch, main and bustle of HBS is high temperature and high pressure pipe, and is the most complicated system of HBS pipeline system. Hot blast pipe is the important tache to achieve high blast temperature and the technical guarantee of stable transferring high temperature blasting. In the design, through HBS piping system stress calculation analysis, the expansion displacement caused by operating temperature, environmental temperature and operating pressure is considered. Low stress pipe design philosophy is adopted. Hot blast pipe is optimized in order to fulfill the 1300 ℃ high temperature blasting requirement. Different structure bellow compensator and tie-rod are arranged reasonably. The bellow compensator position of hot blast branch is arranged between hot blast valve and hot blast main. At the end of hot blast main, pressure equalizing type bellow compensator is arranged to optimize the pipe support and provide technical assurance for hot blast pipe stable operation.

4 Application

Shougang Jingtang No. 1 BF was blown-in and start-up on May 21st, 2009. After blow-in, the production is stable and smooth, and all operation technical parameters keep improving. The maximum daily output is 14245 t/d, and the monthly average productivity is 2.37 t/(m^3 · d). Fuel ratio is 480 kg/t. Coke rate is 269 kg/t. PCI rate is 175 kg/t. Blast temperature is 1300 ℃. All these parameters have reached the expected design level. In order to fully exert the technical advantages of BSK DCHBS, BF operation keeps optimizing and blast temperature is increased steadily. On December 13, 2009, the BF blasting temperature exceeds 1300 ℃, and average blast temperature in December 2009 reaches 1281 ℃. In March 2010, the average blast temperature reached 1300 ℃. The design value of BF blasting temperature at 1300 ℃ continuously and stably with only BF gas is achieved, and new record of huge BF high blast temperature operation practice is created, and reaches the advanced level of worldwide 5000 m^3 grade huge BF high blasting temperature. Table 2 are the main operating technical parameters of No. 1 BF at Shougang Jingtang.

Table 2 Main operating technical parameters of No. 1 BF at Shougang Jingtang

Time	Average daily output/(t · d^{-1})	Productivity/ (t · m^{-3} · d^{-1})	Coke rate/ (kg · t^{-1})	PCI rate/ (kg · m^{-1})	Fuel ratio/ (kg · t^{-1})	Blast temperature/℃	Process energy consumption/ (kg · t^{-1})
2009-05	4840	0.88	551	83	634	914	799
2009-06	7425	1.35	503	62	565	998	538
2009-07	8525	1.55	483	49	532	1063	461
2009-08	11000	2.01	372	94	481	1166	409
2009-09	11660	2.12	354	101	483	1212	419
2009-10	12210	2.22	340	117	488	1262	414
2009-11	12500	2.27	299	145	484	1276	406
2009-12	12694	2.31	288	149	479	1281	393
2010-01	12657	2.30	307	137	482	1259	388
2010-02	12847	2.34	287	161	482	1277	375
2010-03	13035	2.37	269	175	480	1300	373
2010-04	12147	2.21	289	156	482	1275	381

5 Conclusions

1) In Shougang Jingtang 5500 m^3 huge BF, DCHBS technology is integrated and innovated, and the design blast temperature is 1300 ℃. Numerical calculation, physical model and hot simulation test are adopted, and theoretical study on HBS combustion, gas flow and heat transmission process is carried out. 3-D simulation design is adopted. HBS process flow and process layout is optimized. Several HBS high efficiency long campaign life technologies are studied and developed.

2) DCHBS proper and circular ceramic burner design structure is optimized. High performance refractory material is configured reasonably. In order to effectively restrain the HBS shell intercrystalline stress corrosion and control reasonable dome temperature, acid and corrosion proof insulation measures are taken at HBS high temperature area shell and hot pipe inner wall.

3) After blow-in, the monthly average blast temperature of Shougang Jingtang No. 1 BF reaches 1300 ℃ burning only BF gas, creating new record of huge BF high blasting temperature operation and reaching international advanced level of 5000 m^3 grade huge BF high blasting temperature operation.

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