case of $(\beta_{q1}-\beta)=-14^{\circ}30'$ for all the three types of vane.

6. Conclusion

The main experimental results are as follows:

(1) At the shockless entry, there are more chances of cavitation for the round tip vane than for the other type vanes. For the sharp tip vane no cavitation occurs in the experiments.

(2) Except at the shockless entry, in spite of the discrepancy of the vane tip shapes, incipient cavitation occurs in each vane at the same relative velocity and suction head.

And the fact mentioned above are considered to be natural from the pressure distributions on the vane surfaces.

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Utilization of Coal Ash through the Slag Tap Furnace*

By Tatsuo EGUSA**

From the view point of utilization of coal ashes, the production of various by-products—ash-cement, ash-wool and fused phosphate—is undertaken through a small test furnace of a slag-tap firing type. Further described here are the test results and some consideration about the industrial procedure in the future.

These by-products, in their qualities, are comparatively inferior to the like products on the market. They are, however, economically valuable from the point of utilizing the very wastes—coal ashes—as raw materials.

The purpose of applying both sintering and quality-control furnaces for the production of cement and wool lies in eliminating the trouble caused by the load variation unavoidable in the practical boiler operation, and also lies in improving the quality of the by-products themselves⁽¹⁾.

These auxiliary-furnaces, in the present level of development in the fields of industries, are considered the very useful measures for the realization of them in their industrial scale.

1. Introduction

The use of the slag-tap firing process has thrown a progressive light upon its inherent advantages for a boiler furnace as of two-stage or cyclone burning type⁽¹⁾.

However, an emphasis so far has been placed only on the primary features such as ash-treatment, dust prevention, complete combustion, and return

of fly-ash, which are, the original characters of the type of furnace when compared with those of the dry-bottom furnace type.

However, compared with the latter, the former not only makes it possible to a considerable extent to improve the fly-ash properties⁽²⁾, but also delivers particular slags which are obtained from the former type of furnace and includes no trace of unburns.

Thus there is a new field open to a positive development of various raw materials for useful products.

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In this paper, three experiments for the production of ash-cement, ash-wool and fused phosphate are briefly described.

2. Slag-tap furnace of small capacity⁽³⁾

As shown on the left of Fig. 1 (a), the furnace proper is surrounded by a cylindrical steel plate on the outside and is furnished, on the inside, with the furnace wall, consisting of refractory bricks and insulating materials, thus giving the appearance of a horizontal cylinder.

Fluid slag flows out from the exit opening located approximately at the bottom centre of the furnace proper, and is rapidly cooled in a cooling basin. On the other hand, pulverized coal is tangentially injected almost toward the center of the furnace from the front direction of the furnace. In addition, an ignition oil burner is mounted on the center hole at the front wall, which is also used as a hole for inspecting the inside conditions of the furnace during its operation.

The gas cooler acting a role as a boiler is installed next to the rear side of the furnace and is connected to the furnace by means of a flue lined

inside with refractory bricks.

Further, an air-preheater and a dust collector are provided (Fig. 9).

The design features of this furnace are stated as follows: firstly, because of an experimental use, it has no water wall with stud-tubes covered with refractories as an ordinary slag-tap boiler furnace does.

Secondly, the arrangement of burners and the introduction method of combustion air had to be taken into account in order to use the pulverized-coal of the same grain size as those used for an ordinary pulverized coal firing process.

And thirdly, the pulverized-coal firing process was based on the bin feed system.

The coal used for this test, which was of a lower calorific value of 4 500~6 830 kcal/kg, was simultaneously dried and crushed in a dryer of a special type, and then pulverized to a size distribution of 200 mesh under at 30~50 % in the mill and was stored in the pulverized-coal bin. The fuel supply was regulated by an rotary feeder mounted on the outlet of this bunker and the fuel was delivered into the furnace being carried on the primary air injected. The range of fuel supply was 150~280 kg/hr. The corresponding heat generation in the furnace was $75\sim160 \times 10^4$ kcal/m³hr.

The start-up was done by an ignition oil burner. It was not until the furnace temperature reached almost at 1000°C, that the fuel was switched to the pulverized-coal. The preheating time was almost 20~30 minutes. Within an hour after the fuel was switched, slag began to flow, and during this period the furnace temperature was gradually increased and stabilized. The temperature measured at the center of the furnace top reached almost 1 450~1 630°C.

Fig. 1(a) Construction of a small test furnace for slag tap firing

Fig. 1 (b) Front view of test furnace

3. Production of ash-cement⁽⁴⁾

The work in this test was done to some extent of industrial scale and the use of any specific kind of raw coal was not considered, thus making the experiment condition as practicable as possible.

3.1 Granular slag

As for the coal-ash analysis, in particular the three components of it, Al_2O_3 , SiO_2 and CaO , fortunately the analysis for about 70 % of Japanese coal drop in the composition range of Al_2O_3 ; 20~40 %, CaO ; 0~20 %, and of SiO_2 ; rest. (Fig. 2)

Though the ideal composition of Al_2O_3 ; SiO_2 ; CaO =20; 30; 50 must be an unique target for cement production⁽⁵⁾, the composition of granular slag as a raw material falls in the aforesaid range and so practically, only one content of CaO is so

observed and controlled as to take 50% as a standard value, which means Al_2O_3 ; SiO_2 ; CaO = 10~25; 40~25; 50. Thus an effort was paid to secure as near the target value as possible. A variety of coals as indicated on Table 1 were burnt with proper addition of lime in the test furnace. As a result, particular slags of approximately the standard composition were obtained (Table 1).

However, when trying to admix such a large quantity of lime in the test furnace, several difficulties were found to arise actually as follows;

(1) When admixed in a powdered state, lime is difficult to be mixed with the molten slag within the combustion furnace, that is, its remarkable amount tends to be entrained together with fly ash.

(2) When thrown in a crushed state (of larger grain sizes), an uniform mixture is not obtained.

(3) The mixing of a large quantity of lime affects the firing and fusion condition in the furnace.

(4) As the lime content increases, the molten slag becomes of a dense alkalinity and affect the life of the refractory wall.

3.2 Sintering furnace

In view of the necessary qualification, to secure the maintenance of a high temperature, an excellent heat economy and an efficient completion of the operation with a heat loss as less as possible, the selection of a sintering furnace construction was considered to be imperative.

As for the supply system of raw materials, there will be no essential difference between the batch and continuous systems, since this test object

Fusion temperature of assorted coal ashes			
●	1 150—1 200	△	1 350—1 400
○	1 200—1 250	▼	1 400—1 450
×	1 250—1 300	▽	1 450—1 500
▲	1 300—1 350	∇	1 500—

Point A ● final composition

Line $\overline{BC}$ reference composition
standard composition

Fig. 2 Composition diagram referring to three elements— SiO_2 , CaO , Al_2O_3 —of coal ash in Japan

Table 1 Composition list of raw materials and their final values required for ash cement manufacture
Compositions of raw coals and ashes

		Miike high grade fine-coal	Takahagi Specially washed fine-coal	Yoshima coal	Hujita coal
Industrial analysis	calorific heat	6 840	5 000	4 930	3 630
	moisture	0.85	15.50	13.40	17.90
	volatile	37.70	37.80	33.70	27.30
	fixed carbon	42.20	32.20	32.90	28.60
	ash	19.25	14.50	20.00	26.20
	sulfur	3.12	0.35	—	—
Ash chemical composition	Al_2O_3	19.64	26.39	24.73	21.01
	SiO_2	43.80	43.60	31.48	37.60
	CaO	13.08	5.76	11.08	5.60
	Fe_2O_3	11.61	5.19	6.89	10.65
	other	16.87	19.06	25.82	25.14
3-Components compositions of granulated slag					
Al_2O_3		25.65	34.80	36.75	32.70
SiO_2		57.27	57.60	46.80	58.60
CaO		17.08	7.60	16.45	8.70
3-Components compositions upon addition of CaO					
CaO addition		65.90	84.80	67.10	82.60
Al_2O_3		15.50	18.80	21.95	17.90
SiO_2		34.50	31.20	28.05	32.10
CaO		50.00	50.00	50.00	50.00

is nothing but the effect of the sintering operation upon the granular slag. The construction of the sintering furnace used for this test is shown in Fig. 3. The assembly gives an outlook of a combined cylinder, which consists of three parts of upper, middle and lower section.

The upper section is the combustion room with stud-walls covered with plastic refractory and with an oil burner attached tangentially to the hood on the room, in which the combustion gas passes downward with a spiral motion. The middle section is the operation room, in which a grating is placed at its bottom, and there was piled on the grating three layers of refractory lumps *A*, raw materials *B* and fuel *C*.

The sintering temperature is measured almost at the middle layer of the raw materials. The lower section is the cooling room, in which a spray cooler is provided for cooling purpose in the upper part, and the lower part of which is immersed in the water tank and thus the cooling room is water-sealed. The cooled gas is extracted through the gas-duct by means of the fan.

3.3 Sintering test

To solve a draft problem accompanying the piling of granular slag mixtures over a refractory lumps, the following method was employed; a short pipe of 100 mm diameter and 300 mm length with many small holes perforated around its wall was erected vertically almost at the center of the grating with refractory lumps stacked around the

Fig. 3 Sintering furnace for ash cement manufacture

pipe, and then the layers of raw material and fuel were laminated until the upper brim of the pipe was almost on the same level as that of the layers.

Thus, while the temperature-rise was improved and the required time became much shorter, a new difficulty was encountered in the temperature measurement due to the difficult insertion of the measuring instrument.

Even in the early period of the test when this pipe was not used, there was seen a remarkable difference between the indicated temperatures depending on the location of the thermocouple, so that preliminary tests were conducted at the sintering temperature of about 1400°C and the standard values were obtained and referred to those when the pipe was used.

3.4 Strength test

Out of the material thus sintered, non-sintered portion in the operation room was removed and well-sintered portion was milled for the production of cement.

Based on this cement, standard specimens of rectangular column of 40 mm×40 mm×160 mm were molded in accordance with JIS R 5201 Cement Test Code and were delivered to the strength test.

In addition to two kinds of raw materials for specimens, including Portland cement of 5% (weight) (mark *A*) and 10% (mark *B*) as the stimulant, water is applied for the molding, then cast in the mold, taken out after the lapse of 24 hours, and the tests were conducted on the molded specimens in 7, 14, and 28 days each undergoing air cultivation (Fig. 4).

As a means of comparison of the sintering effects, specimens without sintering of granular

Fig. 4 Mechanical test of ash cement-I

slag were directly made and tested (Fig. 5).

As a result of the performance of the above test series, it was revealed⁽⁶⁾ that the production of ash-cement was quite feasible even for the combustion of low grade coals having a higher ash content, with the use of the granular slag peculiar to the slag-tap furnace in a rather practical way. This has resulted from the improvement of the sintering apparatus, and also has given interesting instructions to a continuous sintering system in the future.

4. Production of ash-wool⁽⁷⁾

As mentioned before, when using the slag-tap furnace the ordinary process is to granulate molten coal-ash in a water tank by having them dropped into it, and extract them in the form of granular slag.

The production of wool in this paper, however, makes a feature of using a quality-control furnace to be mentioned later in place of the tank and of making a direct use of the molten ash in fusion.

4.1 Composition of raw material

Fiber products from coal-ash must be essentially controlled in quality according to the composition of the raw material, even if they are affected by the composition changes resulted from mixing small amounts of various additives (Fig. 2).

Concerning the product, however, the problem lies in its composition referring to those of the conventional inorganic fibers.

An investigation on the three main constituents of $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-RO}$ revealed an interesting results as indicated in Fig. 6; either the natural fibers or the artificial ones fall in each specific range of

Fig. 5 Mechanical test of ash cement-II

composition, respectively. Especially the composition concerned with this particular slag here shows a marked deviation from the others and occupies an unique position. Moreover, the use of the quality-control furnace will not only give the production process a quality-control effect but also make it easy to develop a new prospective field for a composition quite different from those of the conventional inorganic fibers.

4.2 Quality-control furnace

The aim in the use of the quality-control furnace for the production of ash-wool is to receive the flow of the molten slag from the slag-tap furnace, to keep it in a specific high temperature, to mix various additives for the purpose of quality-control and to obtain the necessary properties for the production of fiber.

Consequently the following items must be taken into account;

- (1) Selection of a reasonable type furnace, particularly of a heating method.
- (2) Uniform melting and mixing of additives.
- (3) Elimination of entrained gases and impurities from the molten slag.

As for the selection of the furnace type for this purpose, the use of an electric furnace will be considered and an uniformity of melting and mixing might be expected owing to its high heat release; on the other hand, however, there are some drawbacks regarding the elimination of

Fig. 6 Composition diagram of inorganic fibers based on three components system

entrained impurities and some difficulties in the combined design with the slag-tap furnace.

As for the elimination of the impurities, a good result was acquired by overflowing the molten slag in the pool. Fig. 7 shows an illustration for the construction of the quality control furnace used for this experiment.

4.3 Properties of ash-wool

With respect to the chemical composition and the physical properties, the ash-wool is closely akin to the glass fiber, so that it is far superior to the other natural or artificial fibers.

Because of no effect of crystal water or others impressed, its electric resistance ranges from 25 000 to 30 000 MΩcm, which is a fair match for those of non-alkaline fibers. Its thermal conductivity, too, reaches as high as 0.02~0.03 kcal/m hr°C at 40°C for the fiber with the diameter of 9μ and the bulk specific weight of 0.15 g/cc.

General dimensions for a conventional fiber are less than 10μ in diameter (Fig. 8) and 250~500 mm in length for 5μ diameter. For a fiber of about 10μ diameter, the length will become more than 1 m, thus longer than the rock-wool or slag-wool.

This ash-wool, moreover is featured by such a large elasticity and a low bulk specific weight as the glass-wool is, which are suitable properties for an insulating material. Although, due to the inherent properties of coal-ash the composition and quality of the fiber are naturally controlled within a limitation, the production cost is far lower than that for the glass-wool.

Further improvements on the fiber technique are firmly believed to permit the production of a more superior product.

5. Production of "Fused Phosphate"⁽⁸⁾

5.1 Merits for application⁽⁹⁾

The currently-used production process is to use rock phosphate and serpentine, being heated up to 1400°C in an electric furnace or open-hearth

Fig. 7 Illustrative schema of quality-control furnace

furnace and maintained in a fused condition, and the fused mixture is granulated through rapid-cooling.

The object of this test is to see whether a slag-tap furnace can be used in cooperation with a boiler for this purpose in place of the electric furnace or open-hearth furnace.

(i) Melting performance

The operation of the slag-tap boiler is maintained by an extraordinarily high temperature (1 600~1 700°C) in the furnace, so it requires no particular heat source as in the cases of other furnaces.

Further its ability enabling to meet the melting of the ordinary coal-ash is more than enough for the fusion of the raw material mixture having a much lower melting point. Particularly, in this case, even if the ratio of the mixture to the fuel was increased to 2:1—3:1, a complete firing would be obtained without any disturbance in the firing status of the fuel, thus no evil effect by means of this furnace would result on the product.

(ii) Heat consumption

The comparison of heat consumptions between the practically used melting modes of various types is as follows; for the electric furnace, the heat consumption is 930 kWhr per ton of the product, that is equivalent to 800 kcal per ton. For the open-hearth furnace, though the consumption is almost 170 l/t as mentioned before, it will be lowered to 680 kcal per ton, assuming one half of the consumed heat is recovered from the waste heat loss.

As for the slag-tap furnace, however, even with the use of the pulverized-coal having a calorific value of 5 500 kcal/kg, and also on the

Fig. 8 Microscopic photo of ash wool sample

assumption that the total heat loss comprising the sensible heat required for the melting and the decrease of the boiler efficiency corresponds to about 15 % of the total fuel consumption, the heat loss is nothing but 330 kcal/ton of the product.

(iii) Citric solubility

The fertility of the fused phosphate depends on the value of its citric acid solubility. In this test, a maximum value of 60 % for the solubility being reached, a satisfactory result seems to have been obtained in view of the mixture ratio of this extent (phosphate rock; serpentine=7 : 4)⁽⁸⁾. For a further improvement on the citric acid solubility, a study on the retention time of the molten material in the furnace will be necessary.

5.2 Test performance

For this test was utilized the same slag-tap furnace (Fig. 1), which was used for the experimental productions of ash-cement and ash-wool.

Table 2 shows the fuel and raw material (mixture of rock phosphate and serpentine) used in the test.

1: Test furnace, 2: Quenching basin, 3: Gas cooler, 4: Water inlet, 5: Steam outlet, 6: Air heater, 7: F.D. fan, 8: Dust collector, 9: I.D. fan, 10: Stack, 11: Booster fan, 12: Raw material bin, 13: Pulverized coal bin, 14: Fuel pipe, 15: Feed pipe, 16: Air duct

Fig. 9 Flow sheet of test furnace plant

Table 2 Data on fused-phosphate manufacture test
Fuel and raw-materials

Test series	Coal specimen		Calorific value		Material mixture ratio		Coal;raw material		Moisture (%)		Volatile matter (%)		Fixed carbon (%)		Ash (%)	
1	admixed coal		5 600 kcal/kg		7 : 1		1 : 3		—		—		—			
2	Mitsubishi Bibai coal		6 490 kcal/kg		7 : 4		1 : 3		3.5		35.4		44.8		16.3	
3	Miike fine-coal		6 800 kcal/kg		7 : 4		1 : 2		0.85		37.7		42.2		19.25	

Test No.	Test time	Fuel (kg/hr)	Air temp. (°C)			Gas temp. (°C)			Air Supply (m ³ /min)				Gas volume m ³ /min	Draft, (Aq. mm)		Amp.		
			atmos temp.	primary	secondary	furnace	AH inlet	AH outlet	coal	raw-material	secondary	furnace		I.D.F. inlet	B.F.	F.D.F.	I.D.F.	
1	14.45	244			180	1 300	350	280	6.1	5.6	16.2	110	— 7	—68	19	14.5	19.5	
	15.00	244			220	1 430	370	295	6.1	6.6	16.2	104	— 4	—46	19	15.0	19.0	
	15.15	244			220	1 440	300	270	6.1	6.6	16.2	104	— 8	—22	19	14.5	19.5	
	15.30	244			205	1 410	280	250	6.5	6.6	16.2	96	— 3	—33	19	15.0	20.0	
	15.45	244			205	1 370	280	250	6.5	6.6	16.2	96	— 7	—28	19	15.0	20.0	
2	9.45		22		160	1 150	295	230					—13	—50		14.5	20.0	
	10.00		22		205	1 280	320	260					— 8	—52		14.5	20.0	
	10.30	244	24		245	1 380	435	320	4.4	1.7	19.0	96	— 6	—55	18	14.5	19.0	
	11.00	288	24	62	295	1 450	460	335	6.3	1.7	40.5	104	— 5	—67	18	17	14.0	
	11.30	304	25	83	350	1 460	550	380	6.2	1.7	40.5	110	— 1	—63	18	16	18.5	
	12.00	288	25	85	340	1 440	540	370	6.2	1.7	40.5	110	— 1	—65	17	17	15.0	
	12.30	288	26	84	330	1 420	520	350	6.2	1.7	40.5	110	— 1	—60	17	16	17.0	
3	9.45		21	31	110	1 150	220	170	6.3			96	—11	—55	19	15.0	21.5	
	10.00	244	21	44	195	1 400	340	260	5.5			85	— 1	—30	20	17.5	20.0	
	10.15	280	21	47	215	1 420	365	270	5.5			85	1	—25	20	15.5	20.5	
	10.30	280	21	54	335	1 460	680	390	5.5	6.2		72	1	—19	20	15.0	20.5	
	10.45	244	21	56	260	1 440	375	290	4.9	6.2		72	1	—13	21	14.0	20.5	
	11.00	244	21	54	240	1 410	295	250	4.9	6.1		48	1.5	—10	19	14.5	19.0	
	11.15	184	21	52	205	1 340	350	315	4.9	5.7		48	2.5	— 8	20	15.0	20.5	
	11.30	222	21	52	225	1 360	340	245	4.9	5.7		48	3	— 5	21	15.0	20.0	

The general layout for this plant is presented in Fig. 9. As seen from Fig. 1 (b), (photo), the raw material is provided by the pipe through the inspection hole at the center of the front wall on the furnace. The material mixture coming from the raw material bin was delivered through the burner into the furnace in the same way as the pulverized-coal is generally; however, the ratio of rock phosphate to serpentine in the first test is quite different from the second one (Table 2). Test result for the citric solubility (this fertility is represented by 2 % citric acid soluble phosphoric acid) revealed only 20 %, while at the second test its citric solubility was improved to 40 % as a result of the mixture ratio increase of the raw material to 7 : 4 from 7 : 1.

Accordingly at the third test, the material supply was reduced against the fuel and, further the stirring effect on the material was caused by increasing the primary air and decreasing the secondary one. Thus the citric solubility resulted in the augmentation up to 60 %, which is considered to indicate something like a success to this trial test case.

6. Conclusion

With the use of coal-ash as in the solid and fluid state of granulated and molten slags, respectively, for the by-production of cement, wool and chemical manure having remarkably high, secondary values as of market products, applications of both wide range and superiority hardly comparable with the conventional utilization of coal-ash would be realized and give an impetus for a further positive development on the utilization of the coal having higher ash content.

For the achievement of this aim, besides the use of a special slag-tap furnace which can be used as a boiler combustion furnace as practiced in the test, it was found that the use of an appropriate, additional facilities such as a sintering or quality-control furnace were necessary, too, according to the sort of each by-product, and that its design was above all important.

Only for the production of the fused phosphate, however, the above facilities was not required, yet from the view point of either the overall operation of the whole plant or of the procurement of a product of a higher quality, the actual plant will call for, with an excellent result, a special installation of a receiving furnace of the molten, raw material in place of the water tank located at the bottom opening of the firing furnace, so that the melt tapped therefrom can flow into a water tank.

As a future aim and also a finally developed

phase of the whole system, the firing furnace itself should be furnished with each function for the respective aim without any additional facilities, and in reality, a tide is seen toward this direction of a particular usage.

At the stage up to-day, however, as a high quality of the product has been called for, and a restriction has come from the overall operation of the whole plant, too, thus the additional facilities itself has not decreased the practical value of this project but seem to point to a conservative consideration, and consequently the general utilization should be pushed forward with this process.

In this case, the direct use of a slag-tap furnace of a conventional type, for instance, of a two-stage firing furnace or a cyclone furnace, may be considered. Each of these furnaces, however, was developed essentially as a furnace for boiler whose aim lies in the disposal of the content ash in the form of a granulated slag.

The slag-tap furnace used in this test, though of a small capacity, has not only proven itself to serve as a practical furnace which might take into account the additional facilities for the utilization of the molten slag as a result of its operation, but also given a clue to the project and the practical application of a larger scale.

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