On the Experimental Study of Tuyere Model Ablation and Its Heat Transfer Analysis*

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Synopsis

Through the examination of broken blast furnace tuyeres, it was found that 43% of the failure occurred at upper wall, 45% at lower wall, 12% at side wall and 73% at outer wall of tuyere. The ablated failure occurred at the upper and lower parts of outer and edge walls of tuyere, and the failure of this type exceeded almost 80% of the total failures.

The experimental studies on the ablation failure of blast furnace tuyere were made by using the model tuyeres made of copper, phosphor bronze and brass having the wall thickness of 15 mm. In this study, the velocity of cooling water was kept at 3 to 4 m/sec on the inner surface of model tuyere, and molten iron was poured onto the side wall of model tuyere.

On the basis of the experimental ablation data of model tuyeres, the heat transfer simulation model of ablation was established, in which the heat transfer coefficients were determined by using an electronic computer.

In the heat transfer simulation model, the velocity of cooling water should be over 13 m/sec if the burn-out data published by McAdams is taken into consideration.

Further, an investigation was also made on the effects of the thickness of tuyere wall and its thermal conductivity on the ablation speed of tuyere.

I. Introduction

The failure of the blast furnace tuyeres sometimes hampers the normal blast furnace operation and the productivity of iron will be enormously decreased in case of large blast furnaces.

In this study, the following three items have been examined:

- 1) Investigation of the failure types of blast furnaces
- 2) Experimental studies on the ablation phenomena of model tuyere
- 3) Determination of the ablation characteristics of model tuyere by the heat transfer simulation model

Influences of the material and the thickness of tuyere wall on the ablation characteristics based on the heat transfer model were also studied.

II. Characteristics of the Failure of Our Blast Furnace Tuyeres

1. Configuration of Broken Tuyeres

Table 1 shows the configuration of broken tuyeres

Table 1. Classification of blast furnace tuyere failures, and number of failed tuyeres in each examined period

No. of blast furnace	1	2	3	4	5	6	7	8	Mean value (%)
Period from to	1970.4 1972.3	1970.7 1972.6	1970.1 1971.12	1970.4 1972.3	1970.4 1972.2	1970.9 1972.7	1970.4 1972.3	1971.1 1972.3	
Ablation failure	85	39	92	77	59	100	97	100	80
Worn out failure	15	53	5	16	31	0	3	0	15
Failure by crack	0	8	3	7	10	0	0	0	5

of our blast furnaces for last two years and the configurations of broken tuyeres can be classified by their positions. The configurations of broken tuyeres are different at every blast furnaces, though it should be realized that more than 80% of the failures are by the ablation.

2. Damaged Section of Tuyere

The damaged sections of tuyeres are summarized in Table 2. Among the failures occurred in the peripheral direction, 43% of them occurred at the upper zone, 45% at the lower zone and 12% at the side zone; and among the failures occurred in the radial direction, 73% of them occurred at the outer wall of the tuyeres.

Table 3 shows the enormously ablated failure occurred at the tuyere. From these tables, it is found that the ablated failure mainly occurred at the upper and lower parts of the outer wall and the edge wall of tuyeres, and the number of failures of this type exceeded almost 80% of the total failures.

III. Experiment on the Ablation Failure of Model Tuyere

1. Experimental Apparatus and Its Operations

Figure 1 shows a schematic view of the experimental apparatus. This apparatus consists of two basins, Nos. 1 and 2, and a sliding support of the model tuyeres. Iron of about 20 kg melted by a high-frequency induction furnace was poured into the basin No. 1. The molten iron was poured into the basin No. 2 by opening the stopper of the basin No. 1, and then flowed out to the side wall of the model tuyere through the nozzle (diameter 10 mm) with a constant velocity. After exposing to the molten iron for a certain period of time, the model tuyere was pulled out. The temperature of the molten iron in the basin was 1400°C and the wall thickness of the model tuyere was 15 mm.

The weight of the molten iron poured was about

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Table 2. The failure positions of blast furnace tuyeres

No. of blast furnace		1	2	3	4	5	6	7	8	Mean value (%)
Peripheral direction*1	Upper zone	21	50	11	49	59	73	42	100	43
	Side zone	19	33	13	5	6	13	21	0	12
	Lower zone	60	17	76	46	35	14	37	0	45
Radial direction*2	Outer surface*3	70	44	83	85	67	46	42	100	73
	End surface	17	44	14	8	14	46	38	0	17
	Inner surface*4	13	12	3	7	19	8	20	0	10

Table 3. Upper and lower parts failure, outer and end surface failure, and failure by ablation of the blast furnace tuyere

No. of blast furnace	6	8	7	3	1
Failure by ablation (%)	100	100	97	92	85
Upper and lower parts failure (%)	97	100	79	87	81
Outer and end surface failure (%)	92	100	80	97	87

Fig. 1. Schematic expression of ablation test device for model tuyere

- *1 Peripheral direction
- *2 Radial direction
- *3 Outer surface includes outer edge of end surface
- *4 Inner surface includes inner edge of end surface

10 kg. The flow rate of cooling water was about 13.6 l/min. The velocity of water along the inner surface of the model tuyere was kept at about 3 to 4 m/sec. The period of an experiment was about 10 sec.

2. Experimental Results

The experimental results on the ablated failure obtained by using the model tuyeres are shown in Table 4. Figure 2 shows the results together with the results of the heat transfer simulation model. In this figure the thermal diffusivity is plotted as abscissa and the ablation time which is the ablating period in second as ordinate.

As shown in this figure and Table 4, the model tuyeres made of pure copper were partially ablated by molten iron, but the ablation area was small. On the other hand, the tuyeres made of copper alloys were ablated in a shorter period and the ablated area was large. It was also observed that the model tuyeres made of pure copper without water cooling were ablated in 5 sec but the water cooled model tuyeres could withstand for the period of more than 7 sec as shown in Fig. 2.

IV. Heat Transfer Simulation Model of the Tuyere

In the heat transfer simulation model, it is difficult to evaluate the effect of the diameter (about 10 mm) of the poured molten iron flow.

In the current work, the one-dimensional heat transfer simulation model has therefore been used instead of the three-dimensional model.

1. Calculation of the Quantity of Heat Transferred before the Initiation of Ablation

Figure 3 shows the one-dimensional heat transfer simulation model.

If the temperature of the point MX on the surface of tuyere rises from $T(MX)^{\circ}C$ to $TD(MX)^{\circ}C$ for the period of DT , the quantity of heat added during the period of DT can be expressed by the following equation.

$$Q_0 = C \cdot \rho \cdot V(MX) \cdot [TD(MX) - T(MX)]$$

The quantity of heat conducted from the mesh point MX to MX₁ is expressed as follows.

Table 4. The experimental results of model tuyere ablation by molten iron blowing

Material of tuyere model		Cooling water	Molten iron blowing time (sec)	Ablation area (mm ²)	Temperature of molten iron (°C)
Cu	1	No	5.0	30×50	1 320
Cu	2	Yes	4.0	No	1 340
		Yes	6.0	No	1 330
		Yes	7.2	30×35	1 300
		Yes	7.6	30×35	1 380
PBC (Sn 10%)		Yes	4.0	50×60	1 370
BS (Zn 25%)		Yes	3.0	50×60	1 380
Cu-Cr (Cr 0.5%)		Yes	4.0	20×30	1 270
Cu-Cr-Zr (Cr, Zr 0.5%)		Yes	4.0	40×60	1 230

Fig. 2. The effect of thermal diffusivity on the ablation time of tuyere model

Fig. 3. Heat transfer simulation model at the heating up time before ablation starts

$$Q_1 = \frac{\lambda}{DX} \cdot [T(MX) - T(MX_1)] \cdot DT \cdot S$$

Next the quantity of heat transferred from molten iron to the point MX, Q_2 , is expressed as follows.

$$Q_2 = H_1 \cdot [T_h - T(MX)] \cdot DT \cdot S$$

Substituting these equations into the equation for the heat balance

$$Q_0 = Q_2 - Q_1$$

it becomes as,

$$TD(MX) = T(MX) + \frac{DT \cdot S}{C \cdot \rho \cdot V(MX)} \cdot \left[\frac{\lambda}{DX} \cdot \{T(MX_1) - T(MX)\} + H_1 \cdot \{T_h - T(MX)\} \right]$$

By the same procedure, when the temperature of the point I changes from $T(I)$ to $TD(I)$ for the period of DT , the equation for the heat balance at the inner point I can be expressed as follows.

$$TD(I) = T(I) + \frac{DT \cdot S}{C \cdot \rho \cdot V(I)} \cdot \frac{\lambda}{DX} \cdot [T(I+1) + T(I-1) - 2 \cdot T(I)]$$

At the inner surface of the tuyere, the equation for the heat balance is given as follows.

$$TD(1) = T(1) + \frac{DT \cdot S}{C \cdot \rho \cdot V(1)} \cdot \left[\frac{\lambda}{DX} \cdot \{T(2) - T(1)\} + H_2 \cdot \{T_w - T(1)\} \right]$$

2. Calculation of the Quantity of Heat Transferred before the Termination of Ablation

The quantity of heat necessary for melting a part of mesh point MX can be described by,

$$L \cdot \rho \cdot V(MX)$$

After the temperature of the mesh point MX reached the melting temperature, the quantities of heat transferred are calculated every DT by subtracting the value of $Q_2 - Q_1$ from the given value of $L \cdot \rho \cdot V(MX)$ until the value becomes zero. In these calculations, the temperature $T(MX)$ is kept constant. When the value of $[L \cdot \rho \cdot V(MX) - (Q_2 - Q_1)]$ becomes zero, it is assumed that the ablation of the mesh point MX is finished. Thus the mesh point MX is ablated and washed away by the flow of molten iron, then the new surface mesh point MX_1 is exposed to the flow of molten iron; in the calculation, MX is replaced by MX_1 .

3. Calculation of the Quantity of Heat Transferred during the Period of Ablation

It is not possible to estimate the thickness of molten

copper layer on the surface of tuyere during the period of ablation. Therefore, the over-all heat transfer coefficient (H_3) including the heat transfer effect of molten copper layer was used in this work. The arrangement of mesh point is shown in Fig. 4 where the thickness of molten copper layer is taken as δ . The over-all heat transfer coefficient H_3 of the layer δ can be written by (K/δ) where K is the thermal conductivity of molten copper. Since the value of H_3 can not be obtained easily by the method mentioned above, it is determined by the try and error method using a heat transfer simulation model.

The quantity of heat transferred into the mesh point MX for the period of DT can be expressed as follows.

$$Q_3 = H_3 \cdot \{T_h - T(\text{MX})\} \cdot DT \cdot S$$

The temperature rise at the mesh point on the surface of tuyere can be calculated by using the value of Q_3 . In this calculation taken, the mesh distance DX and the time interval DT are as follows.

$$DX = 1 \text{ mm}$$

$$DT = 1 \times 10^{-5} \text{ hr}$$

V. Results of the Model Experiment and Its Heat Transfer Simulation

The conditions adopted for the model experiment of the ablation of tuyere are as follows.

Wall thickness: 15 mm

Temperature of cooling water: 25°C

Flow rate of cooling water: 13.6 l/min.

Initial temperature of the model tuyere: 20°C

Temperature of molten iron: 1 350°C

Melting temperature of copper: 1 083°C

Latent heat of copper: 49 kcal/kg

Density of copper: 8 960 kg/m³

Thermal conductivity of copper:

340 kcal/mhr°C (at 0°C)

290 kcal/mhr°C (at 1 000°C)

Specific heat of copper: 0.1 kcal/kg°C

1. Determination of the Heat Transfer Coefficient and the Over-all Heat Transfer Coefficient

By the try and error method based on the heat transfer simulation model, a reasonable heat transfer coefficient and an over-all heat transfer coefficient could be obtained, which were agreeable to the experimental results of the model tuyere ablation tests. Table 5 shows the heat transfer coefficient and the overall heat transfer coefficient calculated by the heat transfer simulation model. Since the values obtained for the simulation number 221 are very close to the experimental results, the following values were used for the calculation:

$$H_1 = 13\,000 \text{ kcal/m}^2\text{hr}^\circ\text{C}$$

$$H_2 = 2\,000 \text{ kcal/m}^2\text{hr}^\circ\text{C}$$

$$H_3 = 30\,000 \text{ kcal/m}^2\text{hr}^\circ\text{C}$$

An example of the simulation results of ablation is shown in Fig. 5. It is seen from this figure that the temperature at the inner surface of the tuyere reaches 850°C at the time when the ablation starts on the

Fig. 4. Heat transfer simulation model in the period of ablation proceeds

tuyere surface, so the film boiling starts at the inner surface of the tuyere. The ablation would finish in 0.7 sec after the temperature of the outer surface of tuyere becomes 1 083°C (melting temperature of copper).

The time for the initiation of ablation was determined by observing the change in the flow direction of poured molten iron due to the ablated concave hole on the surface of model tuyere. The completion of ablation was determined by observing the outflow of cooling water from the model tuyere.

VI. Application of the Heat Transfer Simulation Model to the Cooling Effect on the Ablation

As the heat transfer coefficient and the over-all heat transfer coefficient were obtained from the results of the model experiments and the heat transfer simulation model, the effect of intensive cooling on the ablation resistance will be discussed in this section.

1. Influence of the Heat Transfer Coefficient and the Over-all Heat Transfer Coefficient on the Ablation Time

Figure 6 shows an example of the results of the ablation time with various H_1 , H_2 and H_3 . The ablation velocity depends mainly on H_3 . Figure 7 shows the influence of the thermal conductivity of the tuyere material on the ablation time.

2. Influence of the Cooling Effect on the Ablation Time

An example of the results of the influence of H_2 on the ablation time is shown in Fig. 8. In order to prolong the ablation time, the value of H_2 should be more than 9 000 kcal/m² hr°C.

In Fig. 9 the burn-out heat transfer coefficient is plotted as a function of the water velocity for several water temperatures.¹⁾ It is seen from this figure that the temperature at the inner surface is 200°C when the temperature of cooling water is 56°C and the velocity is 12.8 m/sec. Under this condition, the ablation can be prevented. In other words, the velocity of cooling water should be over 12.8 m/sec to prevent the ablation.

Table 5. Tuyere ablation simulation results and experimental data of model tuyere

Simulation number	Heat transfer coefficient			Ablation starts t_0 (sec)	Ablation finished t_1 (sec)	t_1-t_0 (sec)
	H_1	H_2	H_3			
111	11 000	1 000	50 000	6.54	7.44	0.90
112	11 000	1 000	70 000	6.54	7.19	0.65
113	11 000	1 000	90 000	6.54	7.05	0.51
124	11 000	2 000	150 000	7.14	7.41	0.27
125	11 000	2 000	200 000	7.14	7.34	0.20
211	13 000	1 000	30 000	5.42	7.01	1.59
221	13 000	2 000	30 000	5.78	7.45	1.67
232	13 000	3 000	50 000	6.21	7.22	1.01
243	13 000	4 000	70 000	6.67	7.47	1.80
244	13 000	4 000	90 000	6.67	7.32	0.65
245	13 000	4 000	110 000	6.67	7.17	0.50
246	13 000	4 000	150 000	6.67	7.06	0.39
311	15 000	4 000	30 000	5.42	7.36	1.94
322	15 000	7 000	150 000	7.06	7.36	0.30
323	15 000	7 000	200 000	7.06	7.28	0.22
411	17 000	9 000	70 000	6.45	7.24	0.79
412	17 000	9 000	90 000	6.45	7.05	0.60
Model experiment	Cooling water 13.6 l/min			6	7.5	1.5

Fig. 5. Simulation result of tuyere ablation

Generally in the burn-out theory the maximum heat flux is used for burn-out. In the present work, the heat transfer coefficient was used in place of the burn-out heat flux estimated from McAdams' burn-out diagram (Fig. 9).²⁾ The temperature and the velocity of cooling water and the inner surface temperature of the tuyere estimated from McAdams' burn-out diagram are summarized in Table 6. It is seen from this table that the temperature at the inner surface is low when both temperature and the velocity of cooling water are low.

VII. Conclusion

It became obvious from the examination of the broken tuyeres of our blast furnaces that the ablation failure mostly occurred at the upper and lower walls, and at the side wall.

Fig. 6. The relation between ablation and heat transfer coefficients

In order to prevent the ablation of tuyere, some tests were made by using the model tuyeres. Based on the results obtained, the heat transfer model of ablation has been established and the heat transfer coefficients have been calculated by the heat transfer simulation of the model test. From this simulation, have also been examined, the influences of various factors on ablation.

The results obtained are summarized as follows.

(1) The ablation time is estimated as about 7 sec from the experimental studies of the model tuyeres. The heat transfer coefficients are as follows.

$$\begin{aligned} H_1 &= 13\,000 \text{ kcal/m}^2\text{hr}^\circ\text{C} \\ H_2 &= 2\,000 \text{ kcal/m}^2\text{hr}^\circ\text{C} \\ H_3 &= 30\,000 \text{ kcal/m}^2\text{hr}^\circ\text{C} \end{aligned}$$

(2) The velocity of cooling water should be over 13 m/sec in order to prevent the ablation.

Fig. 7. The effect of thermal conductivity of tuyere

Fig. 8. The relation between ablation time and cooling water heat transfer coefficient H_2 and the result of tuyere model ablation test

(3) It is not so effective to use copper alloy with slightly larger thermal conductivity than that of pure copper.

(4) It is desirable to thicken the tuyere wall for the prevention of ablation.

(5) It is desirable that the heat transfer coefficient is over 9 000 kcal/m² hr° C to prevent the ablation.

Nomenclature

C : Specific heat of copper (kcal/kg° C)

Fig. 9. Burn-out condition modified W. H. McAdams' data, and burn-out test result of tuyere model expressed by heat transfer coefficient

Table 6. Burn-out condition between cooling water temperature, cooling water velocity and tuyere inner surface temperature estimated by McAdams' burn-out diagram

Cooling water temperature (°C)	Cooling water velocity (m/sec)	Tuyere inner surface temperature (°C)
56	12.8	200
28	9.3	156
11	7.2	144

- ρ : Density of copper (kg/m³)
 $V(I)$: Volume at the mesh number I (m³)
 λ : Thermal conductivity of copper (kcal/mhr° C)
 DX : Distance of a mesh (m)
 H_1 : Heat transfer coefficient between the molten iron and the surface of tuyere (kcal/m² hr° C)
 T_h : Temperature of the molten iron (°C)
 T_w : Temperature of the cooling water (°C)
 H_2 : Heat transfer coefficient between the cooling water and the inner surface of tuyere (kcal/m² hr° C)
 L : Latent heat of copper (kcal/kg)
 H_3 : Over-all coefficient (kcal/m² hr° C)
 S : Area (m²)

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