POST COMBUSTION TRIALS AT DOFASCO'S
KOBM FURNACE

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ABSTRACT

Post combustion trials were conducted at Dofasco's 300 tonne KOBM furnace as part of the AISI Direct Steelmaking Program. The purpose of the project work was to measure the post combustion ratio (PCR) and heat transfer efficiency (HTE) of the post combustion reaction in a full size steelmaking vessel. A method of calculating PCR and HTE using off gas analysis and gas temperature was developed. The PCR and HTE were determined under normal operating conditions. Trials assessed the effect of lance height, vessel volume, foaming slag and pellet additions on PCR and HTE.

INTRODUCTION

Post Combustion at Dofasco

Dofasco's #2 Melt Shop was converted from LD to the combined blowing KOBM process in August 1987. The 300 tonne KOBM furnace is a state of the art vessel with full computer controlled blowing and a sublance system for dynamic control. It has eight bottom tuyeres for bottom oxygen and lime injection. This vigorous bottom stirring makes metallurgical control of the blowing process independent of the top lance practice allowing greater freedom for post combustion optimization. A complete description of the furnace operation and development has been presented in previous publications1,2,3.

The objective to increase scrap melting capability by enhanced post combustion was an integral part of the conversion to the KOBM. Klöckner, which engineered the KOBM conversion, supplied lance tip designs and technical guidance during the development of a post combustion practice at Dofasco. A post combustion lance practice has been the operating standard since 1989. All of the original development work was completed using a heat and mass balance analysis of the furnace charge and turnaround data as Dofasco did not have off gas analysis capability.

AISI Direct Steelmaking Program

The AISI Direct Steelmaking Program approached Dofasco in November 1988 with a proposal to evaluate post combustion in a large commercial steelmaking vessel. The AISI had determined that a high degree of post combustion and heat transfer were necessary to make direct steelmaking feasible. A key element of the AISI proposal was to evaluate the effect of a foaming slag on post combustion. After some initial trials to verify the feasibility of foaming the slag in the KOBM, a contract project was started by Dofasco for the AISI Direct Steelmaking Program in November 1989.

The purpose of the joint AISI/Dofasco project was to measure the post combustion ratio (PCR) and heat transfer efficiency (HTE) of the post combustion reaction in a full size steelmaking vessel. Specific objectives of the project were;

1) Develop a technique to measure PCR and HTE,
2) Study the effect of process parameters (lance height, slag volume and foaming slag) on PCR and HTE,
3) Obtain industrial data for computer modelling of post combustion4,
4) Gain insight applicable to the AISI direct steelmaking program by adding pellets and coal into a foaming slag,
5) Improve scrap melting in a conventional BOF through post combustion.

All of the specific objectives were achieved during the Dofasco trials with the exception of coal additions. These trials were attempted but cancelled when in-blow coal additions generated hydrogen concentrations in excess of the off gas system safety limits. Approximately 300 trial heats were completed in the overall work.

METHOD

The off gas sampling and analysis equipment necessary to conduct these trials was loaned to Dofasco by the AISI for the duration of the contracted work. The two parameters that were used to assess post combustion performance are the post combustion ratio (PCR) and the heat transfer efficiency (HTE) of the post combustion reaction.
The PCR is defined as:

\[ \text{PCR} = \frac{\%\text{CO}_2 + \%\text{H}_2\text{O}}{\%\text{CO} + \%\text{CO}_2 + \%\text{H}_2 + \%\text{H}_2\text{O}} \times 100 \]  

(1)

The HTE is calculated using the off gas temperature as it leaves the vessel. The HTE is defined as being 100% if the temperature of the off gas leaving the vessel is the same as the temperature of the steel bath at that time. An increase in off gas temperature above the steel bath temperature indicates a loss of energy and therefore a HTE of less than 100%. The reference bath temperature used in the calculations was based on previous measured values from Dofasco's BOF operation.

The PCR and the HTE occurring inside the steelmaking vessel were calculated using the off gas analysis and temperature measured at the top of the furnace off gas duct. The sampling location is shown schematically in Figure 1. The off gas analysis in the furnace was calculated by correcting for the secondary post combustion occurring above the furnace mouth due to reaction with entrained air. The suppressed combustion off gas system at Dofasco has approximately 15% entrained air.

**MEASURED**

- Gas Sample and Temperature
- Hoop Water Flow and Temperature
- Sag Sample
- Argon Tracer

**CALCULATED**

- Gas Flow
- Secondary Post Combustion and Gas Temperature
- Entrained Air
- Primary Post Combustion and Gas Temperature

Figure 1 - Schematic of method used to determine PCR and HTE.

The off gas volume and the volume of entrained air were calculated using a combined argon and nitrogen balance. The main source of argon in the off gas came from argon that was injected into the furnace bottom oxygen supply (20 Nm³/min) to be used as the volume tracer. Other sources of argon are the process oxygen itself and entrained air. Sources of nitrogen include the entrained air and purge nitrogen from various openings (main lance, sublance, etc.) in the off gas system.

The temperature of the off gas inside the furnace was calculated using the temperature measured at the top of the furnace duct and adjusting it for the heat of reaction due to the secondary post combustion above the furnace mouth and the measured heat losses to the duct cooling water.

The off gas analysis and temperature, and the hoop cooling water flow and temperature data were measured continuously throughout each test heat. Every 15 seconds a 'snap shot' was recorded by the existing process computer and stored in an electronic database. The raw data was used as input to a computer program to calculate the PCR and HTE occurring inside the furnace. These values were calculated both for the 'snap shot' or instantaneous condition and as a weighted average (based on gas volume) for the whole heat. An example of the calculated PCR for a typical heat is shown in Figure 2.

![Figure 2 - Example of calculated post combustion ratio for a typical heat.](image)

The off gas volume and temperature data responded to process changes within 30 seconds. The calculated PCR was therefore sensitive to process changes such as raising the lance. The water in the furnace off gas system, however, takes about 2 minutes to get from inlet to outlet. Therefore to measure a change in HTE for a large installation like Dofasco's any change in operation must be maintained for several minutes.

In addition to the PCR data generated from the off gas analysis and temperature, other charge information was also recovered from the KOBM process computer to be used in an existing Dofasco heat and mass balance program. In this way the results from the off gas information could be verified by means of actual thermal and mass balances from the converter.
RESULTS AND DISCUSSION

1. MEASUREMENT OF PCR AND HTE

Post Combustion Ratio

The instantaneous value of PCR is plotted as a function of blowing time in Figure 3. The average value of PCR for the complete heat was determined to be 16.1% as shown in Table I. The shape of the PCR curve reflects the changes that occur in the decarburization rate through the blow. The decarburization rate, shown in Figure 4, shows clearly the stable period of maximum decarburization in the middle of the blow.

<table>
<thead>
<tr>
<th>PCR (%)</th>
<th>Mean</th>
<th>Std. Dev.</th>
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<tbody>
<tr>
<td>PCR (%)</td>
<td>16.1</td>
<td>1.3</td>
</tr>
<tr>
<td>HTE (%)</td>
<td>43.8</td>
<td>5.7</td>
</tr>
</tbody>
</table>

In the early part of the blow (0-5 min.) the PCR is high due to the low decarburization rate and a corresponding excess of oxygen. In the middle of the blow (6-14 min.) the decarburization rate is relatively constant and the PCR is steadily decreasing. In the final stages of the blow the decarburization rate decreases and the PCR increases again. The results illustrated in Figure 3 only show the beginning and middle periods of the blow as data from the final minutes was highly erratic due to heat specific conditions. The unstable period of PCR at the beginning and end of the heat are also affected by lance and hood skirt movement. For the batch operation of BOF steelmaking the stable period during the middle of the blow is the best period to show the effect of process changes on PCR.

The gradually decreasing PCR during stable decarburization can be related to the increase in gas velocity in the furnace. As the bath temperature increases through the blow so does the gas volume. Increased gas volume means decreased gas residence time and reduced available time for combustion of CO gas to CO₂ inside the vessel. Gas residence time is defined as the volume of gas generated per unit time divided by the free inner volume of the furnace.

Heat Transfer Efficiency

The average value of HTE for a heat was calculated to be 43.8% as shown in Table I. This result was verified by the observed correlation between tap temperature and PCR. The tap temperature increases 4.9 °C for each 1% increase in PCR. The theoretical value for 100% efficiency is 10.4 °C for 1% PCR. Therefore the HTE based on actual tap temperature measurement is 47% which is in good agreement with the value of 43.8 % calculated from the off gas analysis.

The shape of the HTE curve is analogous to the shape of the PCR curve described above and is shown in Figure 5. The HTE shows great variability at the beginning and end of the heat when the...
Decarburization rate is increasing or decreasing. During the period of stable decarburization (6-14 min.) the HTE steadily decreases. This decrease in HTE may be caused by two factors:

- the increasing gas velocity in the furnace,
- the increasing bath temperature.

The reduced gas residence time due to increased gas velocity reduces the time for heat transfer to the bath. The increasing bath temperature decreases the driving force for energy transfer from the gas phase to the steel bath. In the batch BOF process it is not possible to separate gas velocity from gas and bath temperature effects since both are increasing as the blowing time increases. As a result, during these trials it was not possible to establish the exact reason for the decrease in PCR and HTE during the middle period of the blow.

### Table II

<table>
<thead>
<tr>
<th>Lance Height (metres)</th>
<th>PCR (%)</th>
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<tr>
<td>3</td>
<td>10.8</td>
</tr>
<tr>
<td>4</td>
<td>15.7</td>
</tr>
<tr>
<td>5</td>
<td>21.6</td>
</tr>
</tbody>
</table>

Raising the lance height by one metre (4m to 5m) resulted in an increase in PCR of 5.9%. No change was noted in the HTE. With no change in the HTE the extra energy generated by higher PCR results in increased refractory wear to the furnace top cone. This result is reflected in Dofasco’s normal operating practice. The standard lance height of 4 metres was chosen as a balance between increased PCR for scrap melting and acceptable refractory wear in the furnace mouth and cone.

### Vessel Volume

The post combustion trials were conducted over a six month period that encompassed the last half of one campaign and the first half of the next. It was observed that the PCR increased with increasing furnace life (volume), see Figure 6. The HTE did not change with furnace life. Over the course of a campaign the furnace inner diameter at the slag line increases from 5.7 to 7.0 metres contributing to a furnace volume increase of about 40%. The increasing vessel volume increases the gas residence time in the furnace thereby increasing the time available for the post combustion of the off gas.

### Figure 5

**Instantaneous heat transfer efficiency for normal blowing practice.**
(No. of observations = 39)

### Figure 6

**Effect of furnace life on post combustion ratio.**

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2. **EFFECT OF PROCESS PARAMETERS**

#### Lance Height

Normal Dofasco KOBM practice uses a top lance height of 4 metres above the bath which is lowered to 3 metres shortly before the sublance measurement, as shown in Figure 11. To measure the effect on PCR and HTE the lance height was varied from 3 metres to the maximum height of 5 metres. Results are shown below for a trial run over 34 consecutive heats;
The increase in PCR was verified by the results of a heat and mass balance calculation as shown in Table III. The difference in PCR at different periods in the campaign life are statistically significant. This observation must be considered when comparing PCR results from different periods over the furnace life.

### Table III

<table>
<thead>
<tr>
<th>Furnace Life (Heats)</th>
<th>Off Gas Analysis</th>
<th>Heat &amp; Mass Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 500</td>
<td>13.1</td>
<td>14.0</td>
</tr>
<tr>
<td>1000 - 1500</td>
<td>14.8</td>
<td>15.3</td>
</tr>
<tr>
<td>2000 - 2500</td>
<td>16.1</td>
<td>16.6</td>
</tr>
</tbody>
</table>

**Foaming Slag**

The normal operating practice at Dofasco uses bottom lime injection to rapidly obtain a V-ratio (ratio of CaO/SiO₂) of 2.0 within the first 2-4 minutes of the heat. The resulting slag shows little foaming and no slopping. A foaming slag was created in the furnace by reducing the amount of powdered lime injected early in the heat. The foaming was controlled over the 6-12 minute period of the blow by small additions (1-2 kg/tonne) of bottom lime when it appeared that the furnace was going to slop. The slag foaming could not be controlled on heats with large slag volumes. Trials were limited to heats with a relatively low slag volume (<35 kg/tonne) by selecting heats with hot metal silicon less than 0.40%. A typical range of hot metal silicon at Dofasco is 0.2% to 0.6%. After 12 minutes of the blow the remainder of the fluxes, bottom lime and top charged dolime (calcined dolomitic limestone), were added to complete the heat following standard practice.

Samples of the foaming slag were taken during the blow by lowering a chain 2-3 metres into the furnace mouth. Samples of slag that showed "good" foaming behaviour had a V-ratio that ranged between 1.2 to 1.5, see Figure 7.

A "good" foaming heat was achieved when a small amount of slag was observed sporadically spurting or running out of the taphole or over the mouth of the furnace. After practising this slag foaming technique a "good" foam could be achieved 70% of the time. No foaming was observed for 20% of the heats, and violent slopping and heavy emissions resulted 10% of the time. The slopping heats forced the furnace operators to bottom inject additional lime. This action stopped the slopping and slag foaming within 30 seconds.

The effect of a foaming slag on PCR and HTE is shown in Figures 8 and 9 and compared in Table IV. The PCR was observed to decrease during the foaming slag period. The PCR returned to the normal level when the foaming slag was destroyed. The HTE

![Figure 7 - Foaming slag control - V-Ratio vs. Hot metal silicon.](image1)

![Figure 8 - Effect of a foaming slag on PCR.](image2)

![Figure 9 - Effect of a foaming slag on HTE.](image3)
During the foaming slag trials Dofasco's Environmental Control Department measured the particulate emission rate from the KOBM. There was a reduction in the particulate emission rate during the period of slag foaming by a maximum of 59% at the 6 minute point, see Figure 10.

3) APPLICATION OF RESULTS

Pellet Addition

Iron ore pellets were added to the foaming slag to simulate the direct smelting phenomenon of interest to the AISI Direct Steelmaking Program. Ore additions of 2000 kg were made from a bin above the furnace at a rate of 800-1000 kg/min. Pellets were added during the 6-8 minute period of the blow when the bath carbon was 2-3%.

The off gas analysis indicated that the PCR and HTE were no different from foaming slag heats without pellet additions. The ore additions caused an increase in the decarburization rate over the 6-10 minute period due to the reduction of the iron oxide. Based on the observed increase in the decarburization rate, the reduction rate of the pellets was about 500 kg/min.

Modified Lance Practice

Knowledge gained by analyzing PCR and HTE through the blow lead to a modification in the standard lance practice. The lance practice was modified to maximize PCR during the early part of the blow when HTE is highest. The lance height was increased to 5m for the first 8 minutes of the blow, 4 metres from 8-15 minutes, and at 3 metres for the remainder of the blow, see Figure 11. The objective was to maximize the energy recovered to the bath for scrap melting while minimizing refractory wear in the furnace cone area due to excess energy from post combustion during periods of low HTE.
### Table V
Effect of Modified Lance Practice on PCR

<table>
<thead>
<tr>
<th>Lance Practice</th>
<th>PCR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Normal</td>
<td>10</td>
</tr>
<tr>
<td>Modified</td>
<td>11</td>
</tr>
</tbody>
</table>

Results obtained using the off gas analyzer showed an increase in the average PCR of 4.3% by using the modified practice. An extended trial compared the normal and modified lance practices over an eight week period. The heat and mass balance calculation was used to evaluate the results. Scrap melting was shown to increase by +0.6% of the furnace charge.

### ACKNOWLEDGMENTS

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### REFERENCES


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