Note

Identification of the Combustion Degree of Oil in the Blast Furnace Tuyeres

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1. Background

In spite of its ancient origin the blast furnace has remained competitive against other alternative processes for production of iron for primary steelmaking. A reason for this is that several inherent bottlenecks have been removed gradually through ingenious modifications of the process, e.g., by introducing metallurgical coke in the 18th century, pre-heating of the blast in hot stoves in the 19th century, and burden agglomeration in the 20th century. Another change during the last century was the introduction of auxiliary reductants, mainly pulverized coal, oil and natural gas, injected along with the blast, often in combination with oxygen enrichment. Today, when alternative processes for production of iron for steelmaking emerge, an economic operation of the blast furnace under high productivity and low fuel rate often requires that a considerable part of the charged coke be replaced by injected fuels.^{1,2)} However, at high injection rates, and particularly for the case of injection of heavy (and viscous) oil,³⁾ the extent of combustion may be a limiting factor.⁴⁾ The combustion can be enhanced by raised temperature, turbulence, and simultaneous injection of oxygen, or by appropriate design of the injection equipment, e.g., using co-axial oxy-oil lances.^{3,5)} Because of the deficiency of oxygen in the raceways the conversion of oil droplets may still be incomplete. A possible remedy is to allow the combustion to take place partly within the tuyeres by supplying the oil (and oxygen) at some distance from the tuyere tip. Some authors have discussed the implications of gasification and combustion of supplementary fuels (mainly coal) in the tuyeres,⁶⁾ but the conditions at partial combustion of heavy oil in the region have not attracted much attention; this is the topic of the present short note. By a simplified model of the conditions in combination with measurements from experiments at an operating industrial blast furnace it is demonstrated that about half of the injected oil may be burned in the tuyeres before entering the raceways.

2. Basic Thermal Conditions of Combustion of Oil in the Tuyeres

In this section, a brief feasibility analysis is carried out to clarify whether the thermal requirements of combustion of oil droplets in the tuyeres are fulfilled. Consider a spherical oil droplet with diameter d_p , formed after injection through the lance and exposed to the atmosphere in the tuyere. The drag force acting upon the droplet in the (main) direction of the flow, x , is

$$F = \frac{\pi d_p^2}{4} f_d \frac{\rho(w - w_p)^2}{2} \dots\dots\dots(1)$$

where f_d is the drag coefficient and symbols without subscript refer to the gas while symbols with subscript p refer to the droplet. Combining $F = m_p a_p$ with Eq. (1), the acceleration, a_p , of the droplet can be expressed as

$$a_p = \frac{dw_p}{dx} = \frac{f_d \rho (w - w_p)^2}{32 \rho_p d_p} \dots\dots\dots(2)$$

The surrounding hot blast makes the temperature of the droplet increase, heating the surface of the droplet by both convective and radiative heat transfer, yielding a total heat flux of

$$q = h(T - T_s) + \varepsilon \sigma (T_\infty^4 - T_s^4) \dots\dots\dots(3)$$

where h is the convective heat transfer coefficient, T_s is the droplet surface temperature, T_∞ is the temperature of the surroundings emitting radiation on the droplet and ε is the emissivity of the droplet. Within the droplet heat is transferred by conduction in the radial direction, r . By assuming rotation symmetry the conduction can be described by

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T_p}{\partial r} \right) = \frac{\rho_p c_{p,p}}{\lambda_p} \frac{\partial T_p}{\partial t}; \quad 0 \leq r \leq r_p \dots\dots\dots(4)$$

The possibilities of combustion of oil inside the tuyere can be studied by solving the system of differential and algebraic equations, Eqs. (2)–(4), with typical conditions encountered in the blast furnace tuyeres (blast and initial drop velocities, temperature and thermal properties of the fluids). The convective heat transfer coefficient, h , can be estimated by standard correlations.⁷⁾ Considering drop traveling distances of 0.10...0.20 m and a (quite arbitrarily chosen) temperature of onset of gasification and combustion of $T_c = 873$ K, the results presented in **Fig. 1** were obtained. The figure shows the time required for heating (dashed lines) droplets of different size ($d_p = 100, 150$ and $200 \mu\text{m}$) to $T_s = T_c$ and their residence time (solid lines) at typical blast volume flow rates encountered in the tuyeres of the furnace studied in this work. Since the model only holds for the region where no mass transfer has taken place, it can only be applied to the point where pyrolysis (followed by combustion) starts. The figure tells that, e.g., droplets with $d_p \leq 155 \mu\text{m}$, after formation, are heated enough in 0.15 m. In summary, the brief analysis has shown that the thermal requirements of oil combustion are fulfilled.

3. Simplified Model for Evaluation of Oil Combustion in Tuyeres

Inspired by these findings a simplified model was formulated. Consider the system depicted in **Fig. 2**, where hot blast from the main bustle “1” enters the tuyere through the compensator pipe “2”. Closer to the tuyere tip “4” oil (possibly together with oxygen) is injected through a lance “3”. The air–fuel mixture enters the raceway “5”, where the main combustion takes place. It is not industrial practice to measure the flow rates of blast to individual tuyeres, but the differential pressures between the main bustle pipe and the compensator pipes,

$$\Delta p_{12} = p_1 - p_2 \dots\dots\dots(5)$$

are often monitored. With this information, the volume flow rate of blast accepted by the tuyere can be estimated from

Fig. 1. Heating times (solid lines) and residence times (dashed lines) for spherical oil droplets of different diameters calculated at typical blast velocities encountered in a tuyere. Drop traveling distances: i) $x = 0.10$ m, ii) $x = 0.15$ m, and iii) $x = 0.20$ m.

Fig. 2. Schematic view of the system studied.

Fig. 3. Detailed view of flows and states in the simplified tuyere model.

$$\Delta p_{12} = f_{12} \frac{\rho_2 w_2^2}{2} \quad \text{yielding} \quad \dots\dots\dots (6a)$$

$$\dot{V}_2 = \frac{\pi D^2}{4} \sqrt{\frac{2 \Delta p_{12}}{\rho_2 f_{12}}} \quad \dots\dots\dots (6b)$$

where f_{12} is the friction factor of the section between “1” and “2”, mainly consisting of the loss in the junction. Using this equation, in combination with the results of the theoretical analysis of the combustion conditions, the following simplified approach is taken to describe the tuyere system in **Fig. 3**:

- Hot blast (at pressure p_1) enters the tuyere with a pressure loss, Δp_{12} , in the junction.
- Oil is injected, possibly together with oxygen, through the lance (“3” in **Fig. 2**), which leads to complete combustion

of a fraction, χ , of the oil. The combustion to carbon dioxide and water is motivated by the excess of oxygen in the tuyere, and the remaining oil is assumed to be neither pyrolyzed nor combusted.

- The combustion considerably raises the gas temperature (from T_2 to T_4 , solved for from a heat balance assuming adiabatic conditions) and also increases the molar flow rate, both contributing to an increase in the volume flow rate, (from $\dot{V}_2$ to $\dot{V}_4$). These factors, together with a possible decrease in cross-section area, yield a dramatically increased velocity, w_4 , in the tuyere tip.
- The pressure in the raceway is

$$p_5 = p_4 - \Delta p_{45} \quad \text{with} \quad \Delta p_{45} = f_{45} \frac{\rho_4 w_4^2}{2} \quad \dots\dots\dots (7)$$

where the friction factor at the tuyere tip, f_{45} , comes from the aperture.

- The remaining oil, together with coke, is combusted in the raceway. Because of oxygen deficit in this region, the combustion products are taken to be CO and H_2 (and N_2). By solving mass and energy balances for raceway, assuming adiabatic conditions, the temperature (T_5), composition and volume ($\dot{V}_5$) of the bosh gas

can be determined. The flow from the raceway is assumed to be governed by^{8,9)}

$$K = \frac{p_5^2 - p_0^2}{\dot{V}_5^{1.7}} \quad \dots\dots\dots (8)$$

where p_0 is the top gas pressure and K is the internal gas resistance of the bed.

4. Identification Procedure

With the simplified model outlined above, it is possible to evaluate the combustion degree of oil in the tuyeres by an experimental procedure. Process data from the 560 m³ blast furnace of Fundia Wire OyAb in Koverhar, Finland, which is operated with 100% pellets at a productivity of about 3 t/m³ d, typically using 450 kg/thm of fuel including 100 kg/thm of heavy oil. The oil is injected into 16 tuyeres through co-axial lances with core flow of oil and annular flow of oxygen, both flow rates being controlled.

From the prevailing point of operation the lance of a selected tuyere was pushed forwards to approach the absolute vicinity of the tuyere tip, was kept at this position for some time (about 10 min) and was then pulled back to its original position. The idea of this procedure, which was repeated a number of times, was to record on the change in blast accepted by the tuyere in question when shifting between a state where a fraction of the oil was burned and a state where (practically) no oil was burned inside the tuyere. When the lance is at the tuyere tip, the value of the internal gas resistance factor, K , of Eq. (8) can be determined with ($\dot{V}_4 = \dot{V}_2$, disregarding the negligibly small volume occupied by the oil beam). Taking K to be constant at the instant of the perturbation, the recorded change in the differential pressure Δp_{12} reflects a change in the blast volume accepted by the tuyere, obtained from Eq. (6b), and an estimate of the combustion degree, χ , that satisfies Eqs. (7) and (8) can now be determined by iteration.

5. Results and Conclusions

Three experiments have been undertaken, the first one (for tuyere #11) in late June and the two remaining ones (for tuyeres #10 and #6) in early December, 2001. The evolution of the differential pressures during the experiments, depicted in **Fig. 4**, reveals that the position of the lance

Fig. 4. Differential pressures recorded during the three trial periods. Downward and upward arrows ($\downarrow$, $\uparrow$) denote pushing the lance to the tuyere tip and pulling it back to its original position, respectively.

Table 1. Key variables and combustion degrees determined from experimental data of Fig. 4. Downward and upward arrows ($\downarrow$, $\uparrow$) denote pushing the lance to the tuyere tip and pulling it back to its original position, respectively.

Key variables	Unit	Experiment					
		i=1		i=2		i=3	
Total blast volume, $\dot{V}_{tot}$	m ³ (n)/h	54 200		58 100		58 100	
Blast volume* to tuyere, $\dot{V}_2$	m ³ (n)/s	1.05		0.90		0.99	
Blast temperature, T_1	°C	1220		1193		1193	
Blast pressure, p_1	bar	1.75		1.95		1.95	
Specific oil rate	kg/thm	102		122		122	
Oxygen content of blast	%	27.4		26.9		26.9	
		Combustion degree					
Perturbation		$\chi_{1,\downarrow}$	$\chi_{1,\uparrow}$	$\chi_{2,\downarrow}$	$\chi_{2,\uparrow}$	$\chi_{3,\downarrow}$	$\chi_{3,\uparrow}$
j = 1	-	0.37	0.35	0.58	0.54	0.50	0.56
j = 2	-	0.38	0.36	0.44	0.43	0.57	0.61
j = 3	-	0.40	0.31	0.56	0.61	0.46	0.49
j = 4	-	0.33	0.45	0.49	0.43	0.49	Y
j = 5	-	0.30	0.29	0.54	0.49	0.54	0.55
j = 6	-	0.39	0.40	0.46	0.40	0.57	0.55
Mean combustion degree		0.36		0.50		0.54	

Y) Ambiguous value caused by large pressure fluctuation

*) Average value for the tuyere in question with oil lance in original position

plays an important role for the burning of the oil in the tuyeres. From each perturbation (pushing the lance in and pulling it back) we obtain two estimates of χ , which may differ because all process variables are subject to continuous change. **Table 1** presents some central operation parameters during the days of the experiments, as well as the model's interpretation of the combustion degrees of the injected oil. Even though the results show some scattering the perturbations must be considered to have yielded reproducible results within each series. In terms of combustion degrees of reaction (R1), the model indicates that between of one and two thirds of the oil would burn within the tuyeres. The different magnitude of the combustion degrees in the first and the later experiments can be partly explained by differences in the blast pressure; the higher value of p_1 in

Fig. 5. Effect of the degree of oil combustion, χ , in the tuyere at constant blast pressure, p_1 , and internal resistance factor of the bed, K . Upper panel: blast volume accepted by the tuyere, $\dot{V}_2$ (solid line), and gas velocity, w_4 , in the tuyere tip (dashed line). Lower panel: differential pressure, Δp_{12} (solid line), and blast temperature in the tuyere tip, T_4 (dashed line). Nomenclature follows Figs. 2 and 3.

Experiments 2 and 3 yield lower gas flow rates and a longer residence time of the droplets in the tuyeres (cf. Fig. 1). This improves the basic conditions for combustion. Naturally, the individual behavior of each tuyere, lance and raceway should also be kept in mind.

In evaluating the implications of these findings, it should be noted that the resulting combustion degrees lead to extreme conditions at the tuyere tips. For fixed values of the blast pressure, p_1 , and the gas resistance factor, K , the blast temperature and velocity in the tuyere tip as well as the blast accepted by the tuyere and the differential pressure, estimated by the model, have been depicted in **Fig. 5** with respect to the oil combustion degree, χ . The figure shows that gas temperatures and velocities exceeding $2000^{\circ}C$ and 400 m/s , respectively, can be reached in the tuyere tip. This is expected to have a severe impact on the coke in the raceway, causing considerable grinding action, with accumulation of large amounts of coke fines in the birds nest as a result. A general recommendation is, therefore, to increase the tuyere diameter if combustion of oil within the tuyeres is desired.

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