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Progress Report

DESIGN STUDIES OF OXYGEN NOZZLES

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OBJECTIVE

The work reported herein was carried out in order that recommendations could be made to the Ford Motor Company regarding suitable nozzles for use in their Basic Oxygen Furnaces.

The particular objective of this current phase of the work was the development of a single nozzle which would pass 22,000 cubic feet of oxygen per minute at a nozzle inlet pressure of 108 psig. It was also required that the nozzle produce a well behaved jet when operated at flow rates of from 14,000 to 22,000 cubic feet per minute and that at any particular flow rate in this range the jet would have nearly the maximum penetration capability possible at that flow rate.

SUMMARY

Several nozzles have been fabricated and tested. All of these have the same throat area, this area being fixed by the required maximum flow rate for the given pressure available at the lance tip. The variables tested were throat length, exit area, exit shape, and expansion angle.

Data are presented showing the characteristics of the jet produced by the various nozzles tested. In particular, data for the recommended nozzle are shown which give some of the jet characteristics of interest in the operation of Basic Oxygen Furnaces.

As a result of this work a nozzle of the following internal dimensions is recommended for use in the Ford Motor Company Basic Oxygen Furnaces:

Throat Diameter	3.644 inches
Throat Length (Approx.)	1 inch
Divergence Half Angle	5 degrees
Exit Diameter (i.e., the diameter at the end of the 5 degree divergent section)	4.317 inches

The other dimensions and general shapes are as shown in Figure 2 of this report and as shown in Detail "A" of Ford Motor Company's Drawing Number 63-130F-13.

NOZZLE EQUATIONS

The ideal flow equation for a sonic or supersonic nozzle is:

$$W = \frac{0.56\ P_o\ A^*}{\sqrt{T_o}} \tag{1}$$

where W = oxygen flow rate in pounds per second

P_o = total or stagnation pressure upstream of the nozzle - psia

A^* = nozzle throat area - square inches

T_o = total or stagnation temperature upstream of the nozzle - degrees Rankine ($^oR = {}^oF + 460$)

The weight of one cubic foot of oxygen at standard conditions (14.7 psia and 60°F or 520°R) is 0.0844 lbs. Therefore Equation (1) can be expressed in terms of Q, standard cubic feet of oxygen per minute.

$$Q = 398.2\ \frac{P_o A^*}{\sqrt{T_o}} \tag{2}$$

If we assume that the temperature of the oxygen supplied to the nozzle is 60°F (i.e., 520° Rankine):

$$Q = 17.45\ P_o A^* \tag{3}$$

The accuracy of this assumption is not critical since a change in the oxygen supply temperature by as much as 50° would introduce an error of only about 5%.

It is generally necessary to include a Nozzle Coefficient and a velocity of approach correction in the above equations for practical application. Previous nozzle tests have shown that a nozzle coefficient of 0.97 is a reasonable value. The velocity of approach correction for the particular lance-nozzle configuration under consideration is 1.013. The net result is that Equation (3) becomes:

$$Q = 17.15\ P_d A^* \qquad (4)$$

where P_d = the nozzle driving pressure, i. e., the static pressure in the line upstream of the nozzle - pounds per square inch, absolute. For the nozzle-lance configuration under consideration Equation (4) should be accurate within one or two percent, provided the oxygen supply temperature is near the 60°F assumed.

NOZZLE DESIGN

A basic requirement[1] for the nozzle under consideration is that it be able to pass 22,000 standard cubic feet of oxygen per minute at a static pressure immediately upstream of the nozzle of not over 108 psig (122.7 psia). Since it was also desired that the momentum of the oxygen leaving the nozzle should be as great as possible, this upper limit of nozzle driving pressure (P_d) was assumed rather than some lower driving pressure. Thus by Equation (4)

$$A^* = \frac{22,000}{(17.15)(122.7)} = 10.44 \text{ square inches}$$

or (5)

$$D^* = \text{Throat Diameter} = 3.644 \text{ inches}$$

The nozzles used in this test program were made with throat diameters of 3.644 ± .001 inches.

A variation of 1/2 of 1% in the throat diameter of a nozzle results in a change in driving pressure of only 1% at any particular flow rate (in the range of flow conditions of interest here). Thus, a single nozzle having a throat diameter of 3.644 ± .010 inches should be suitable for Ford's Basic Oxygen Furnaces.

It is clear from Equation (4) that, for a particular nozzle, the oxygen flow rate varies directly with the nozzle driving pressure. Figure 1 is a plot of oxygen flow rate through a nozzle having a diameter of 3.644 inches versus the nozzle driving pressure. The equation for Figure 1 is:

$$Q = 179.2\,P_d \tag{6}$$

where P_d is in pounds per square inch <u>absolute</u>.

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[1] Established by the Ford Motor Company

After the throat diameter of a supersonic nozzle is determined the exit diameter of the nozzle can be considered. As a gas passes through a supersonic nozzle the velocity increases and the pressure decreases. The maximum effective momentum at the nozzle exit is achieved when the pressure in the jet right at the nozzle exit just equals the pressure of the atmosphere into which the nozzle is exhausting. The pressure at the nozzle exit is (within limits) determined by the pressure upstream of the nozzle and the ratio of nozzle exit area to nozzle throat area. A given nozzle can therefore, be "ideally" designed for only one upstream pressure (assuming the nozzle exhausts into a fixed pressure - here assumed to be atmospheric pressure).

Previous nozzle work has indicated that in general a nozzle operating at a pressure higher than its design pressure produces a better behaved jet than does a nozzle operated at a pressure below its design pressure.

For this reason, most of the nozzle configurations tested had the correct exit area (D_e = 4.317 in.) for a flow rate of 14,000 CFM. (The throat area of all nozzles was established for a flow rate of 22,000 CFM at 108 psig at the nozzle.)

Nozzles were also fabricated and tested which had the correct exit area (D_e = 4.859 in.) for the higher flow rate. These tests served as a check on the results of previous work cited above.

Nozzles having no divergence section at all were also built and checked for the sake of comparison.

The length of a nozzle throat and the angle of divergence can be chosen more arbitrarily than can throat diameter and exit diameter. Throat lengths of about 3/4, 1 and 3 1/2 inches were employed in this series of tests. In the converging-diverging nozzles two divergent half-angles were employed, namely 5^o and 10^o.

A "nose piece" was attached to many of the nozzles tested to simulate that portion of the external part of the end oxygen lance which might conceivably affect the oxygen jet. This nose piece was made to conform to the end part of the lance shown in Detail "A" of Ford Motor Company Drawing Number 63-BOF-13.

A conical convergent section having a half-angle of 30° was chosen for the nozzles to be tested in this work. This resulted in a reasonably short converging section while avoiding the expense of the contouring which might be needed if a very short converging section were to be used. Table I lists the nozzle configurations tested.

TEST PROCEDURE AND RESULTS

The flow rate of air through a given nozzle will be only slightly different from the flow rate of oxygen through the same nozzle, provided the pressure and temperature ahead of the nozzle are the same in both cases. Since, however, the momentum of the gas leaving the nozzle will be the same for both oxygen and air, it is to be expected that the results of nozzle tests made with air will be applicable to a nozzle which is blowing oxygen. Previous tests have been conducted which confirmed the interchangeability of data from tests using oxygen and air. For these reasons, all of the nozzle tests discussed in this report were made with air.

Clearly these tests do not account for the difference between the environment encountered by a jet in room air and that encountered by a jet in an Oxygen Converter.

The air for these nozzle tests was obtained from the high pressure system available to the Aircraft Propulsion Laboratory. This system has a storage capacity of 320 cubic feet at a pressure of 2500 psi. The air is supplied to this system by a 250 h. p. compressor.

After necessary plumbing changes were made to this system, air flow rates of up to about 22, 000 SCFM were obtainable, on a blowdown basis.

Individual nozzle tests were made by opening the main control valve until a flow rate of about 22, 000 SCFM (i. e. , a nozzle driving pressure, P_d, of about 108 psig) was obtained. Without further valve changes the flow rate would slowly fall until a flow rate of about 14, 000 SCFM (i. e. , a P_d of 64 psig) was reached whereupon the run was terminated. Each such run lasted about 45 seconds. For the jet profile data a pressure rake, composed of 23 total head tubes, was used to sense the pressures in the jet stream. The individual tubes were connected to a multibank mercury manometer. Photographs were then made of the manometer at various times during any one run. In the vertical plane three tubes were mounted above and below the center probe as a constant check on horizontal centering of the rake assembly. The center tube was also connected to one channel of a Foxboro type 40-RP recorder. By this method a simultaneous recording was made of the driving pressure ahead of the nozzle and the maximum impact pressure of the jet. (Temperature in the air supply pipe was also recorded.) The pressure data so obtained has been plotted, for all the nozzle configurations listed in Table I, in Figures 3, 7, 8, 9, and 10. Figure 3 shows centerline pressure versus driving pressure at various blowing distances for the 5^{O} short throat nozzle with nosepiece. Figure 4 is centerline pressure versus blowing distance at constant driving pressure for this same nozzle, and Figure 5 shows pressure profile in the jet for this nozzle. Figure 6 is the "computed" penetration versus blowing distance, at three flow rates, again for the 5^{O} short throat nozzle with nosepiece. This is based on room air tests only and does not take into account the various factors present in an actual oxygen converter.

Jet diameter for recommended nozzle, except in the immediate vicinity of the nozzle exit, can be represented approximately by the equation

$$D_j = .25x$$

where D_j = jet diameter, feet
x = blowing distance, feet

based on room air tests.

CONCLUSIONS AND RECOMMENDATIONS

Twelve different nozzle configurations have been tested. Of all these, the nozzle described by Figure 2 produced the best behaved jet and also produced a jet of nearly optimum penetration capability. All of the other eleven nozzle configurations tested resulted in either a jet of less penetration capability or a jet which was not well behaved, i. e., the penetration capability (impact pressure) increased in an erratic manner as the flow rate increased.

The nozzle shown in Figure 2 fulfills the basic requirements established for the nozzle design studies covered by this report.

Although there are certainly other nozzle configurations which should perform as well as the Recommended Nozzle shown in Figure 2, it is not anticipated that any substantial improvement could be expected.

Figure 2 does not specify the nature of the various "corners" in the nozzle, but it should be understood that all corners should be well rounded except the corner at the end of the conical divergent section which can be reasonably sharp.

The values of the "computed" penetration of the oxygen jet into the molten iron bath shown by Figure 6 should be used as a rough guide only. Appreciably greater penetration should be expected.