CANADA

PRESSURE DISTRIBUTION WITHIN A VACUUM ARC FURNACE

by

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Pressure Distribution within a Vacuum Arc Furnace

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ABSTRACT

The pressure distribution within a continuously evacuated, consumable electrode arc furnace was determined when a variable leak was placed in the melting region of the furnace. This pressure distribution agreed both with that obtained from a simplified calculation based on the kinetic theory of gases and with that obtained during the melting of mild steel electrodes.

Johnson, *et al.* (1) have shown that the arc characteristics and the melting rate in a consumable electrode, vacuum arc furnace depend on a number of variables, including the gas pressure within the furnace. In current practice the pressure is usually measured at some point in the body of the furnace and not in the region of the arc. Since gas is evolved from most metals during melting the pressure in the region of the arc will be higher than that in the body of the furnace.

In the present work the pressure in the region of the arc has been calculated and measured in a simple simulated melting system and results have been compared with similar pressure measurements obtained during the melting of steel electrodes.

Apparatus and Experimental

The experiments were conducted in the furnace described by Rylski and Kinsey (2) and shown schematically in Fig. 1 Gas pressure was measured at the top of the mould and at a point 30 cm below the top by means of thermocouple vacuum gauges and probe tubes which passed through vacum seals in a side port of the furnace. The probes were constructed from 1 cm diameter tubing and were the same length so that their response to pressure fluctuations would be the same. The pressure in the body of the furnace was measured with an Alphatron ionization gauge. The Alphatron ionization gauge was initially calibrated against a McLeod gauge. Prior to each experiment the thermocouple gauges were calibrated *in situ* against the Alphatron ionization gauge by isolating the furnace from the pumps and admitting air to a series of static pressures. These recalibrations of the thermocouple gauges were reproducible within $\pm 1\mu$ Hg pressure.

To simulate the evolution of gas during melting, a needle valve was connected to the base of the mould. The lower probe was about 9 cm from the base plate of the mould. The leak rate for each setting of the needle valve was determined from the known volume of the furnace and the observed rate of increase in pressure when the furnace was isolated from the pumps. After each adjustment to a specified leak rate, it was necessary to allow 30 sec to elapse for the attainment of equilibrium, before measuring the pressure at the three points.

The pressure distribution within the mould was determined while melting a mild steel electrode which contained 0.13% C, 0.01% N, 0.005% O and less than 0.0001% H. During these experiments the pressure was measured only at the top and at the lower part of the mould and the temperature of the tip of the lower probe was measured by means of a thermocouple attached to it. When the arc was struck, the pressure rose quickly but, after about 90

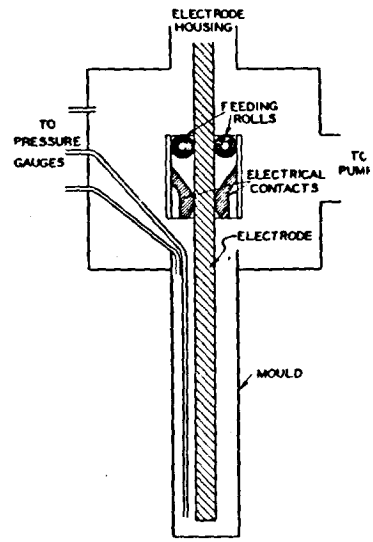

Fig. 1. Arrangement for measurement of pressure distribution within the arc furnace.

sec, dropped to a steady value when the feed rate was uniform. Before melting, the lower probe was about 4 cm from the melting zone and no melting of this probe occurred when a steady feed rate of the electrode was quickly attained and the arc length kept short.

Results

Simulated melting.—The distributions of pressure, for two electrode and two mould sizes, are shown as functions of the leak rate in Fig. 2-5. When the 11.5 cm diameter mould was used the pressure difference between the top and the lower part of the mould was not very large and was only slightly affected by the electrode size. Relatively large pressure differences were obtained when the 7.5 cm diameter mould was used and these differences varied considerably with the size of the electrode.

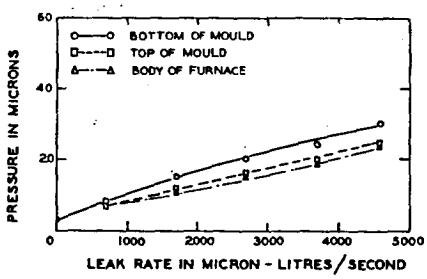

Fig. 2. Distribution in pressure for an electrode 3.2 cm x 3.2 cm in a mould of 11.5 cm diameter.

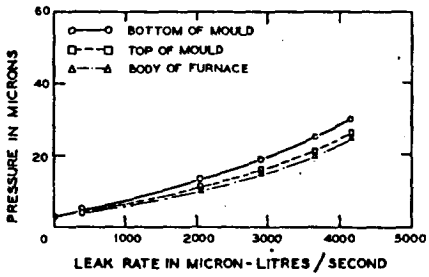

Fig. 3. Distribution in pressure for an electrode 3.2 cm x 4.9 cm in a mould of 11.5 cm diameter.

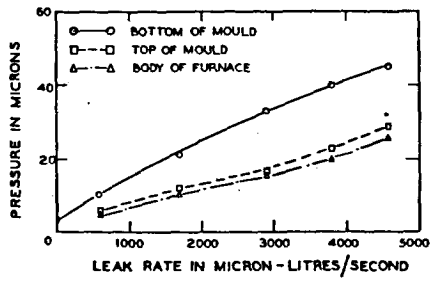

Fig. 4. Distribution in pressure for an electrode 3.2 cm x 3.2 cm in a mould of 7.5 cm diameter.

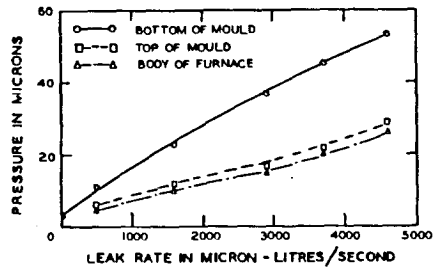

Fig. 5. Distribution in pressure for an electrode 3.2 cm x 4.9 cm in a mould of 7.5 cm diameter.

Actual melting.—To avoid melting the lower probe, the pressure distribution in the mould was measured only when melting a 3.2 cm square steel electrode in the 11.5 cm diameter mould. Different rates of gas evolution were obtained by melting the same steel electrode at different rates. The rate of melting was controlled by the amount of current used in the arc. Because of the temperature gradient along the lower probe, there was a pressure gradient along this probe.

If the mean free path of the molecules in the hot region of the probe is greater than the diameter of the probe, then the pressure P_A in the hot region is related to the pressure P_B measured at the gauge by:

$$P_A/P_B = \sqrt{T_A/T_B} \qquad (I)$$

where T_A is the temperature of the tip of the probe and T_B is the temperature of the gauge.

In the present case the mean free path of the molecules was approximately the same as the diameter of the probe and Eq. (I) gave too high a value for the pressure in the hot region. A correction factor, which depends on the ratio of mean free path to probe diameter, for Eq. (I) has been obtained from the results of other workers (3). Table I lists the measured pressures at the top and the lower part of the mould and also the corrected values of the pressure at the lower part of the mould. Once melting started, the temperature of the probe tip rose quickly for approximately 90 sec but in the following 30 sec, when steady pressure readings were obtained, the temperature of the probe tip increased by only 40°K. Variations in temperature of this order of magnitude have little effect on the calculated pressure in the hot region and the relatively steady temperature of the probe tip suggests that the measured temperature should be close to the gas temperature.

Discussion

On the basis of the kinetic theory of gases, Gruber (4) has calculated the pressure at the top of a mould and then the pressure at the lower part of that mould. In calculating the pressure at the top of the mould a formula was used which is applica-

Table I. Distribution of pressure within a mould of 11.5 cm diameter while melting a steel electrode 3.2 cm square

Arc current (amp)	Temperature of probe (°K)	Pressure at lower part of mould (μ of Hg)	Pressure at lower part of mould, corrected for temperature effect (μ of Hg)	Pressure at top of mould (μ of Hg)	Approx. melting rate (kg/min)
1200	1200	9	15	13	0.5
1500	1200	10	16	14	0.6
1800	1200	13	21	19	0.9
2100	1100	22	32	28	1.3

ble only to a thin aperture, the dimensions of which are small compared with those of the vessel from which the flow is occurring. This leads to considerably lower pressures than are encountered in practice and thus the pressure drop along the mould as calculated by Gruber will be in error.

The following calculation of the pressure drop along the mould during the simulated melting experiments is based on an equation describing the flow of gas through a simple pipe and this is modified to allow for the presence of the electrode. The flow of gas through a circular pipe over a wide range of pressures is described by a semi-empirical equation developed by Knudsen (5) and for air flowing at 25°C may be written in the following form:

$$\frac{Q}{P_1 - P_2} = Cm \left\{ 0.0145\, a(P_1 + P_2) + \frac{1 + 0.246\, a(P_1 + P_2)}{1 + 0.304\, a(P_1 + P_2)} \right\} \quad \text{(II)}$$

where Q is the quantity of gas flowing through the pipe, in micron-liters per second; P_1 and P_2 are the pressures at the ends of the pipe, in microns; Cm is the conductance of the pipe when molecular flow is occurring, in liters per second; and a is the radius of the pipe, in centimeters.

For the present case of an electrode within the circular mould, the average separation between the mould and the electrode was used rather than the radius of the mould. The molecular conductance of any duct, for air flowing at room temperature, may be calculated from the following formula (6):

$$Cm = 61.8\, K \frac{A^2}{BL} \quad \text{(III)}$$

where A is the cross-sectional area of the duct, in square centimeters; BL is the surface area of the walls of the duct, in square centimeters; and K is a constant equal to 1.1 for an annular duct (6) similar to the present arrangement of an electrode in a mould.

From the observed leak rate and the pressure at the top of the mould the pressure drop along the mould was calculated. These values are given in Table II together with those measured during the simulated melting experiments. Reasonable agreement is evident between the calculated and the experimental values. Particular attention is drawn to the close agreement between the values of the pressure difference measured in the actual melting experiments with those measured during the simulated melting experiments. It is possible to compare these two sets of results because the H content of the steel used in the melting experiments is so low. The gases evolved during the melting experiments are mainly N and O or CO. Since these gases have physical properties similar to those of air, the response of the thermocouple vacuum gauges and the conditions of flow in the mould are similar in the two sets of experiments.

Table II. Pressure drop along mould of 11.5 cm diameter containing an electrode 3.2 cm square

Pressure at top of mould (μ of Hg)	Measured pressure drop during simulated melting (μ of Hg)	Calculated pressure drop for simulated melting (μ of Hg)	Measured pressure drop while melting (μ of Hg)
13	3	2.2	2
14	3	2.5	2
19	4	2.7	2
28	4	3.0	4

The flow of gas depends not only on the conditions already mentioned but also on the temperature of the gas. Therefore it might be expected that, in actual melting experiments where the flow is occurring in both a pressure gradient and a temperature gradient, the pressure drop along the mould would be considerably different from that during a simulated melting experiment where the flow is occurring in a pressure gradient alone. One reason for the close agreement may be that the water cooling of the mould cooled the gas quickly and the flow of gas through the mould occurred essentially at an uniform temperature.

The present work shows that the pressure drop along the mould of a consumable-electrode vacuum arc furnace can be measured in simulated melting experiments or can be calculated if the rate of gas evolution in the region of the arc and the pressure at the top of the mould are known. It also shows that if high pressures in the melting region of vacuum arc furnaces, with the accompanying troublesome glow discharges, are to be avoided it is essential that sufficient free space be provided between the electrode and the mould to ensure rapid removal of the gases evolved during melting.

Particularly when melting Ti, and other similar metals, it is possible that some gas (mainly H) will be evolved from the electrode some distance above the melting zone in the furnace as well as in the melting zone. Such evolution above the melting zone will tend to reduce the pressure gradient along the mould.

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Any discussion of this paper will appear in a Discussion Section to be published in the December 1958 JOURNAL.

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