Nozzle Pressure during Stream Degassing*

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I. Introduction

Stream degassing process has been used for the removal of hydrogen from molten metal as well as for the production of very low carbon steel. During this process the metal containing gas forming solutes is discharged through a nozzle into a low pressure environment so that the solutes become supersaturated with respect to their surroundings.

Although semi-quantitative measurements were carried out in the laboratory on the degassing of molten steel,¹⁾ problems of containment made it difficult to obtain reliable and extensive data with this system. More quantitative measurements were made on the removal of oxygen from molten silver.²⁾ The latter experiments confirmed that two-phase flow occurred within the nozzle and that there was a critical downstream pressure in the vacuum tank (about 180 Torr with the straight nozzle of 4.8 mm dia.). Any further decrease in the downstream pressure below this value had no effect on the flow rate since the decrease in pressure was not transmitted to the upstream. This phenomenon, which is frequently encountered in single- and two-phase compressible flow, is known as 'choking'.

It was then felt that direct measurements of the pressure at the nozzle exit was desirable with molten metals. The pressure measurement at the mid-point of nozzles was also hoped in order to obtain some idea of the pressure gradient. This information could be useful in establishing in which region of the nozzle nucleation begins.

II. Experiment

The general apparatus for the test is shown in Fig. 1. Silver was melted, saturated to a required level with oxygen and discharged almost exactly as described previously.²⁾ The only difference was the procedure for pressure measurements as follows:

Since the range of pressures was expected to be 2 to 500 Torr, a pressure transducer was used. This transducer was connected with a pressure tapping (0.8 mm dia.) in the nozzle through a line which was kept full of nitrogen gas. The output from the transducer was sent to an ultraviolet recorder. Prior to discharge the pressure in the tapping line was adjusted to be close to but slightly higher (30 to 50 Torr) than the value expected in the silver melt. This

was achieved by keeping the automatic valve and the needle valve open just before the discharge to allow nitrogen to pass through the measurement line. Then the system was checked by closing the automatic valve manually to shut off the nitrogen supply. The pressure indicated by the transducer decreased very rapidly and reached the value of pressure in the vacuum chamber within 0.02 sec (see Fig. 2 (a)). Raising the stopper rod to start discharge for the actual run closed the automatic valve and resulted in a sudden drop of pressure which soon approached the value in the silver melt. Thereafter, the pressure continued to fall at a steady rate, reflecting the drop in the head of silver in the container (see Fig. 2 (b)). The experiment was terminated by replacing the stopper rod back into the nozzle. However, this had no effect on the automatic valve which remained closed until reopened manually. If the pressure tapping was not blocked and if the pressure in the nozzle had been higher than that in the vacuum chamber, the reading

Fig. 1. General sketch of tundish, including arrangement for pressure measurement

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Fig. 2. Schematic illustration of pressure transducer output obtained on the recorder

on the transducer dropped rapidly to the value of pressure in the vacuum chamber on stopping the discharge (see Fig. 2 (b)).

Accurate measurement of the flow rate was also vital, so three separate methods were used,²⁾ namely the measurement of firstly the drop in the level of silver during a known time, secondly the time taken for silver surface to travel the distance between two probes a fixed distance apart and thirdly the change in buoyancy on a partially immersed sinker. The first two methods were usually used together and provided a check (the difference was less than $\pm 2\%$).

III. Results and Discussion

1. Oxygen Saturated Silver

Typical results of pressure measurements for the 4.8 mm dia. nozzle with the pressure tapping at the exit are shown in Fig. 3. These cover tank pressures of 12 and 100 Torr. Figure 4 compares the flow rate at a given tank pressure with those using a standard 4.8 mm nozzle.²⁾ The curve includes results for pressure drops of 500 to 600 Torr, which correspond to tank pressures of 200 to 300 Torr. However, these experiments were not satisfactory, because the presence of pressure tapping led to interference of the flow, shown up by the lower flow rates. Therefore, the results of pressure measurement for tank pressures of 200 Torr and above were not shown. High speed camera pictures of the streams of oxygen saturated silver are given at various tank pressures in Photo. 1.

These results confirmed that the pressure at the

(a) Tank pressure 12 Torr, oxygen saturated silver, 4.8 mm dia. nozzles

(b) Tank pressure 100 Torr, oxygen saturated silver, 4.8 mm dia. nozzles

Fig. 3. Results of pressure measurements.

Fig. 4. Flow rate measurements in nozzles with a pressure tapping at the exit compared with those in nozzles without a pressure tapping, 4.8 mm dia. nozzles. Oxygen saturated silver.

nozzle exit was considerably in excess of that in the vacuum chamber. Reference to the following equation²⁾ shows that with suitable values for K and C_{fm} , it is possible to calculate P_2 .

$$P_a + \rho_l gh - (1 + k^2)P_2 = \frac{G^2}{2\rho_l} \left(1 + K + 4C_{fm} \cdot \frac{l}{d} \right) \dots (1)$$

where, P_a : atmospheric pressure
 ρ_l : liquid density
 h : silver head
 P_2 : the static pressure at the nozzle exit
 k : correction factor due to surface tension

Photo. 1.
Photographs of oxygen saturated streams flowing into the vacuum tank at various pressures from 4.8 mm dia. nozzles. Note the sudden expansion of the stream at the exit at the lower tank pressures.

effect

K : entry loss coefficient

G : mass flux density

C_{fm} : friction factor

l/d : the length-diameter ratio.

This calculation had been done⁴⁾ and the results are shown in Fig. 3. (see the broken lines) for a value of the friction factor of 0.005.

It is evident that the predicted pressure is very close to the experimental value for this value of friction factor, which incidentally is the figure proposed by Wallis³⁾ for homogeneous bubbly flow. An alternative, but not an independent, calculation to prove choking would be to use the following equation²⁾ to evaluate the the Mach number.

$$M^2 = \frac{G^2 \cdot \delta_2}{k^2 P_2 \rho_l} \dots \dots \dots (2)$$

where δ_2 is the void ratio at the exit (gas volume/liquid volume).

This void ratio had been evaluated experimentally²⁾ as 0.13 and hence the Mach number was calculated to lie between 0.9 and 1.0. Considering the assumptions involved and the possibilities of nitrogen injection and other difficulties associated with pressure measurement, it is reasonable to assume that the stream attained sonic velocity at the exit, thus providing confirmation of the model described previously.²⁾

The 2.4 mm dia. nozzle behaved similarly to the larger one, although reproducibility was less satisfactory. If, as is almost certain, nitrogen injection influenced the results, the effect may well be more severe in the smaller nozzle.

2. Degassed Silver

When degassed silver was discharged, the pressure rapidly approached the downstream value in the vacuum chamber. No significant difference was observed between the two nozzle sizes, and the presence of a pressure tapping aperture in the nozzle wall did not change the relationship between the pressure drop and the flow rate that was observed for standard nozzle without pressure tapping. Thus, it was confirmed that the exit pressure for the single-phase incompressible flow was equalized to the pressure in the vacuum chamber.

IV. Problems and Difficulties

This system of pressure measurement was quite useful for presenting the strong evidence of choking for gas-metal two-phase flow. However, significant problems and difficulties were also encountered in some cases. If the pressure in the line prior to the start of a run was less than that of the silver in the nozzle, the metal would enter the connecting line through the pressure tapping. In a laboratory apparatus, this aperture of the tapping was small, so that the metal flow rate would be far too slow for sufficient metal to enter the line to compress the gas therein to the same pressure as that in the nozzle. In actual practice, the aperture quickly became blocked (see Fig. 2 (d)). On the other hand, if at the start of the experiment the pressure in the line was above that in the nozzle, gas was injected from the tapping line into the metal stream. When this injection was severe the flow pattern was changed leading to the false results (see Fig. 2 (c)). Thus, the design of the pressure measuring system was critical.⁴⁾ The dead

volume had to be reduced to a minimum so as to limit the quantity of gas injected into the system and to avoid any delay in reaching a steady state. However if the apertures and line sizes were too small, frictional effects could render the response sluggish. In the present system, the dead volume was measured to be 4 cm³ and about 99% of the pressure change was observed within 0.4 sec at 200 Torr and 1 080°C.⁴⁾ From these results, the injection rate at steady state was calculated to be 0.1 cm³ and was compared with the oxygen flow rate which was evaluated from the void ratio. The proportion of the injection rate was calculated to be 1.1% of the oxygen flow rate.⁴⁾

In spite of these careful preparations, the results were not satisfactory for exit tapping nozzles at tank pressures above 200 Torr and for mid-point tapping nozzles. In these cases, the flow rates were different from those in standard nozzles without pressure tapings. The gas injection was no doubt interfered with the flow, particularly which was in the sensitive state just as in the transition state from subsonic to sonic region.

In summary, completely satisfactory results were obtained only for oxygen saturated silver using exit tapping nozzles at low tank pressures. Application of the basic technique employed in this work has been found encouraging in the molten steel system.⁵⁾

V. Conclusions

The observations on choked two-phase flow reported earlier were confirmed by pressure measurements made at the nozzle exit. The pressures were much

higher than that of downstream in the tank and agreed with theoretical prediction.

The measurements of static pressure in the flow of a molten metal at 1 100°C posed experimental problems. Careful design and operation made it possible to measure the exit pressure in the nozzle by pressure tapping for oxygen saturated silver flow. In this case, the flow was not unduly interfered with since flow rates were nearly the same in nozzles with and without pressure tapping.

Break up of the stream in the cases when bubble nucleation occurred in the nozzle was caused by the sudden expansion of the bubbles in the flow as they moved from the nozzle exit into the vacuum chamber.

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