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GAS ENTRAINMENT BY PLUNGING LIQUID JETS

by

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SUMMARY

The gas entrainment produced when a coherent liquid jet plunges into a liquid bath is of interest in those processes where chemical reaction occurs between the liquid in the bath and the entrained gas. Following a literature survey it became apparent that most theories present an inadequate explanation of the process. From recent work it appeared possible that the jet surface and the boundary layer conditions upstream of the jet nozzle could be significant variables in the process.

Experimental equipment was designed to investigate the effect of boundary layer development upstream of the jet nozzle on the entrainment process. Data from these experiments, here presented graphically indicated that the more developed boundary layer was associated with a greater gas entrainment for both "smooth" and "rough" jets in the coherent region.

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INTRODUCTION

Jets of liquid which plunge either under the influence of gravity or under the influence of some pressure force exist in almost all processing industries in some form or other. Associated with all but the lowest velocity jets which plunge through an atmosphere into a bath of the same liquid, is gas entrainment by the jet into the liquid bath.

In the steel industry the problem is especially important because of the great number of operations in which liquid metal is transferred from one vessel to another. In most of these operations the transfer is accomplished by a jet of molten steel plunging through air. Because of the high temperature involved, chemical reaction can and does occur between the molten metal and the gases in the air. This problem is compounded by the face that the gases are carried down into the molten bath by the plunging jet and thus produce impurities in the molten steel bath.

The problem may be extended to any processing industry in which chemical reaction can occur between the liquid which makes up the bath and the plunging jet and the surrounding atmosphere.

Since the overall problem of gas entrainment with plunging liquid jets is of interest to the metallurgical industries, most research in the field has been concentrated on metallurgical applications. These industries are most interested in the overall effects such as jet velocity, jet stability, free jet length and jet nozzle design on the entrainment rate. Recently, research specifically design to examine the fluid mechanics of the system has been carried out by McCarthy, et al (1). Several additional problems have been uncovered by this research, one of the most interesting being the effect of upstream conditions on the entrainment rate. In particular, it appears that the degree of development of a velocity profile in the pipe prior to the jet nozzle could have a significant effect on the entrainment rate. A detailed literature survey may be found in Burgess (2).

The object of this work is to determine the effect of a developing velocity profile in the pipe prior to the jet nozzle on the entrainment rate. It is felt that the degree of development of the pipe flow boundary layer has a significant effect by virtue of the fact that the free jet surface geometry is changed significantly with rearrangement of the internal forces associated with the development of the boundary layer.

EXPERIMENTAL

The experimental system which was studied was that of a water jet plunging through an air atmosphere. This selection was made after considering the equipment design problems and economies associated with other systems. The availability of water, its non-hazardous nature and the fact that other workers in the field have used water/air systems enabled equipment to be designed simply and comparisons to be made with other workers.

The problem to be examined was the effect of a developing velocity profile in the pipe prior to the nozzle on the jet surface characteristics and hency the rate of gas entrainment by the jet. As such, an adequate water supply vessel which could supply jets with velocities up to 60 ft/sec (19.5 m/s) at the nozzle exit and which could ensure a flat velocity profile at the pipe inlet was required. Also a system for collecting and measuring the gas entrained by the jet was required.

Included in the design was a system to prevent vortex formation at the pipe from the water supply vessel, a collection system for the entrained gas and a flow measurement system for the entrained gas using hot wire anemometry techniques.

The overall arrangement of the experimental equipment may be seen in figure (1). The equipment consisted of a water supply vessel which could be pressurised with a compressed air supply. Included in the vessel design were a set of anti-vortex baffles to ensure no vortex action at the pipe inlet. The pipes prior to the nozzles (termed the "lance" pipes) had machined bell-mouthed entries to alleviate vena-contracta effects and the nozzles were flush mounted onto the pipe walls. The jet momentum was sufficient to force the two phase liquid and gas flow along the bubble tube to the shroud. From there, the entrained gas travelled along tubing to the hot wire anemometer. The bath consisted of a 100 gallon (450 ℓ) tank which was adequately fitted with overflow launders and a drain pipe.

The general lance pipe and nozzle design may be found in figure (2). The general arrangement consisted of a bell-mouthed entry to a hydraulically smooth lance pipe and a 22° taper from the lance pipe to the nozzle throat. The nozzle throat consisted of what McCarthy terms a "1 DT" nozzle with the nozzle diameter equalling the throat length.

The lance pipe entry was machined as a bell mouth in order to suppress vena-contracts effects and produce a flat velocity profile at the pipe inlet. This bell mouthed section screwed into the base of the water supply vessel with the anti-swirl baffle immediately above the entry point. A summary of the pipe dimensions is shown below:

Pipe diameters used = 0.485" (12.3 mm)
= 0.993 (25.2 mm)

For each pipe diameter, pipe lengths of 6.0", 12.0" and 24.0" (152 mm, 304 mm, 610 mm) where the pipe length is defined by L on figure (2).

The nozzle consisted of a flus mounted connection to the pipe wall tapering at a 22° angle to the nozzle throat. A summary of the nozzle diameters used is given below:

(a) For the 0.485" diameter pipe,

Nozzle dias. = 0.100" (2.54 mm)
= 0.152" (3.85 mm)

(b) For the 0.993" diameter pipe,

Nozzle dias. = 0.201 (5.1 mm)
and = 0.254 (6.45 mm)

Also, the 0.100" dia. nozzle was machined out to 0.254" when the experimental runs with the 0.100" diameter nozzle were finished.

The material of construction throughout the piping and nozzle construction was brass because of the corrosion resistant properties and the smooth nature of the surfaces.

EXPERIMENTAL PROCEDURE

In order to test the effect of the development of the boundary layer in the pipe prior to the nozzle on the entrainment rate, the combinations of pipelength, nozzle diameter and jet length were tested for two jet velocities. These velocities were selected so that the "smooth" and "rough" jets (1) would be included.

For each combination of pipe length and nozzle diameter a set of experimental observations was taken for jet lengths, increasing from 1/4" to 3" (6.1 mm to 76.2 mm). The free jet length was limited to 3" since larger jets tended to break up and so damped out the effect of upstream boundary layer development. The anemometer noise level and the effects of bath interaction with the jet such as vortex amplification make the actual flow rate difficult to determine. The median of the anemometer reading was used for the characteristic entrainment rate.

Each combination of free jet length, pipe length, pipe diameter and nozzle diameter produced a recorded output for the anemometer for times lasting from approximately one minute to three minutes, depending on jet velocity and nozzle diameter. During these periods of time the efflux time for a volume calibrated section of the supply tank was determined to within 0.1 seconds, the size of the volume calibrated section depending upon the rate of efflux. Using these efflux times the jet velocity, jet Reynolds Number and pipe Reynolds Number were calculated.

The nozzle and pipe length combinations used in the analysis were:

PIPE DIAMETER	PIPE LENGTH	NOZZLE DIAMETER
0.485"	6", 12", 24"	0.100", 0.152"
0.993"	6", 12", 24"	0.201", 0.254"

In addition, the 0.100" nozzle for the 0.485" pipe was remachined in the course of the investigation to 0.254" diameter and the tests repeated. It was found that a residence time of 2 minutes was required after filling the vessel in order to produce reproducible results. This was because upstream turbulence in the vessel was sufficient to produce a turbulent jet which entrained more gas than the jet issuing from a stable supply.

Because of the different lengths of pipe involved, there was the possibility that the extra head of liquid involved between the shortest and longest pipes would add significantly to the jet velocity during an observation. Also, as the level of liquid was constantly falling, the jet velocity would be correspondingly affected. It was found that the difference in head involved in both these cases has an insignificant effect on the entrainment rate.

The first set of results for all the combinations was performed at jet velocities of 35-40 ft/sec (10.7m/s to 12.2m/s). The second set of jet velocities was in the region of 60 ft/sec (18.4 m/s). These two velocities produced jets of different surface properties with correspondingly different entrainment characteristics. These jets were designated "smooth" and "rough" respectively.

In order to support the experimental observations, a photographic analysis of the jets was carried out. The photographs helped in an overall explanation of the mechanism at hand on the jet surface.

DISCUSSION OF EXPERIMENTAL RESULTS

The detailed experimental data is available from the author as a series of tables. Each table consists of a summary of nozzle diameter and pipe length combination, jet length, anemometer reading and entrained gas rate, efflux time for the calibrated section of the vessel, the "jet Reynolds number", jet velocity and pipe Reynolds number. These data may be portrayed as plots of gas entrainment rate against free jet length for a particular jet velocity; pipe diameter and nozzle diameter combination. The length to diameter ratio of the pipe upstream of the nozzle is indicated in the data set by an L/D value for each curve. The results are considered in the categories of smooth and rough jets. Figures 3 and 5 are typical plots.

"SMOOTH" JETS

The "smooth" jet is one in which the surface roughness remains constant over a major portion of the jet length, thus "smooth" is a relative term only and is not definitive of the physical nature of the jet surface.

Figure 3 is typical of the general trend which was observed for the smooth jets. The entrainment rate can be seen to rise to a maximum then fall to what appears to be a constant value. The maximum entrainment is seen to occur at approximately 6 jet diameters from the nozzle and after 10 diameters remains constant. The length of the pipe upstream of the nozzle has a significant effect on both the maximum and final value for the entrainment. It seems that the jet suffers a rearrangement after it leaves the solid boundaries of the pipe and nozzle and this rearrangement causes an increase in the size of surface imperfections. Since the maximum entrainment increases with increased pipe L/D value, this rearrangement of forces associated with the developing boundary layer leads to a more turbulent jet.

Figure 4 shows the essential features of a "smooth" jet as obtained from photographs of the jet surface.

The jet may be divided into three zones from the nozzle exit. In zone one the surface is quite smooth. In zone two the surface irregularities appear in increasing amplitude and wave length as the jet progresses away from the nozzle. In zone three the rearrangement appears complete and the surface irregularities appear to remain constant.

Since the entrainment process is closely associated with cavitation, the shape of the entrainment versus jet length plot is a reflection of the growth and subsequent partial decay of the surface irregularities on the jet. The maximum entrainment rate for each length of the pipe upstream of the nozzle is listed below:

PIPE LENGTH L/D (pipe)	JET LENGTH for Maximum Entrainment L/D (jet)
6	5
12	6
24	7

If the rearrangement of the internal jet forces simply increased the size of the surface irregularities, the maximum entrainment should occur at the same jet length. From the experimental evidence however it seems that the surface irregularities change in both magnitude and wavelength with increasing boundary layer development.

"ROUGH" JETS

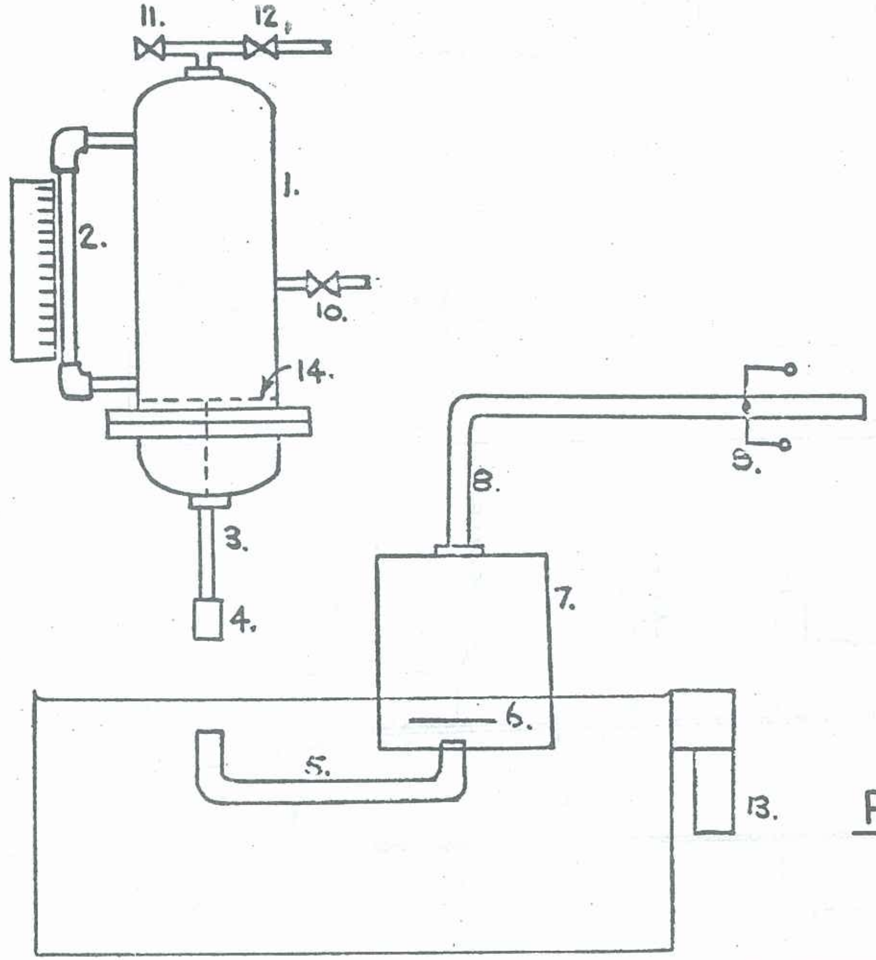
Rough jets are visibly rough and turbulent in nature and the surface irregularities progressively increase with increasing jet length. A typical plot of air entrainment versus jet length for a "rough" jet is shown in fig. 5. In fig. 5, a jet which was "smooth" at a velocity of 37.5 ft/sec (11.4 m/s) is plunging at 60 ft/sec (18.3 m/s). The change in the shape of the curves indicates the change in the nature of the jet surface. The progressive increase in entrainment rate with jet length is indicative of the changed nature of the jet surface. Further the increasing length of pipe upstream of the nozzle seems to indicate an increase in level of the destabling influence and hence the growth of surface irregularities. The values of entrainment rate for increased jet length do not exhibit the maximum shown on the plots for "smooth" jets.

The work is continuing.

REFERENCES

1) McCarthy M., Molloy N.A., Kirchner W.G. and Henderson H.B., "Mechanism of gas bubble entrainment by plunging liquid jets". Trans. Inst. Mining and Metall.(C) 78 (757) (Dec. 1969) 239-241.

2) Burgess, J.W. "Gas entrainment with plunging liquid jets". B.E. Thesis, Univ. of Newcastle 1969.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KEY
1. LIQUID SUPPLY VESSEL.
2. GAUGE GLASS
3. LANCE.
4. NOZZLE
5. BUBBLE TUBE
6. SPLASH BAFFLE
7. SHROUD
8. ENTRAINED GAS OFFTAKE
9. HOT WIRE ANEMOMETER.
10. WATER SUPPLY.
11. VENT
12. AIR PRESSURE SUPPLY.
13. DRAIN
14. ANTI-SWIRL BAFFLE.

FIGURE 1

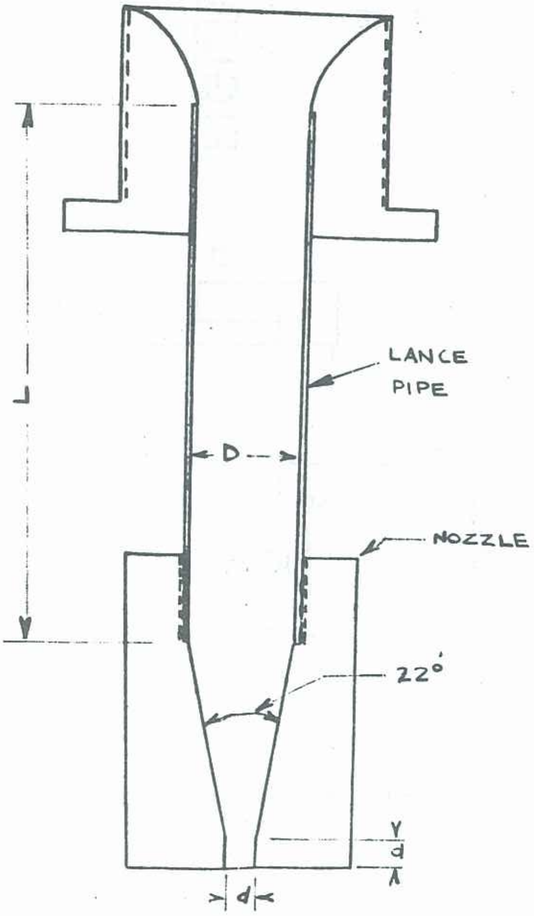

FIGURE 2.

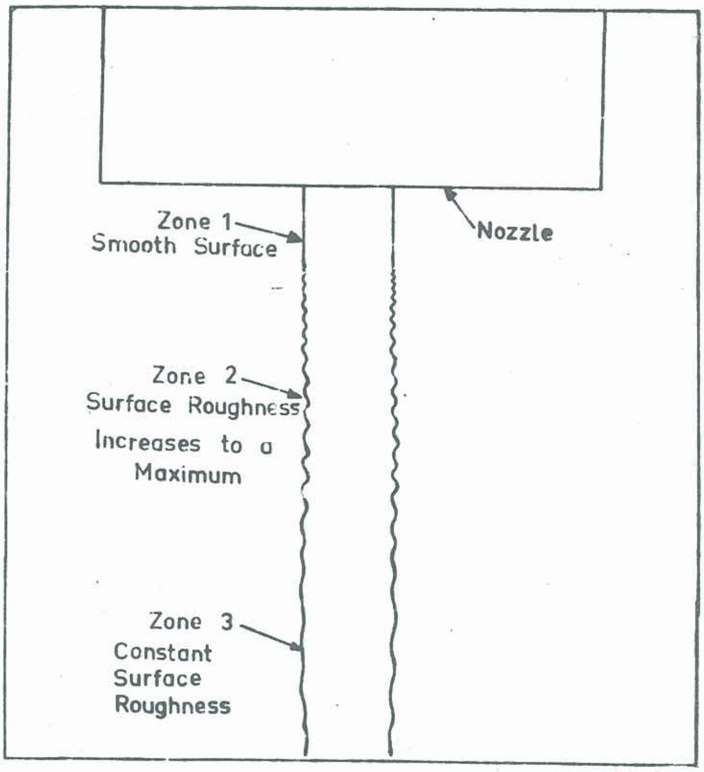

FIGURE 4

Suggested Surface Arrangement For Smooth Jets

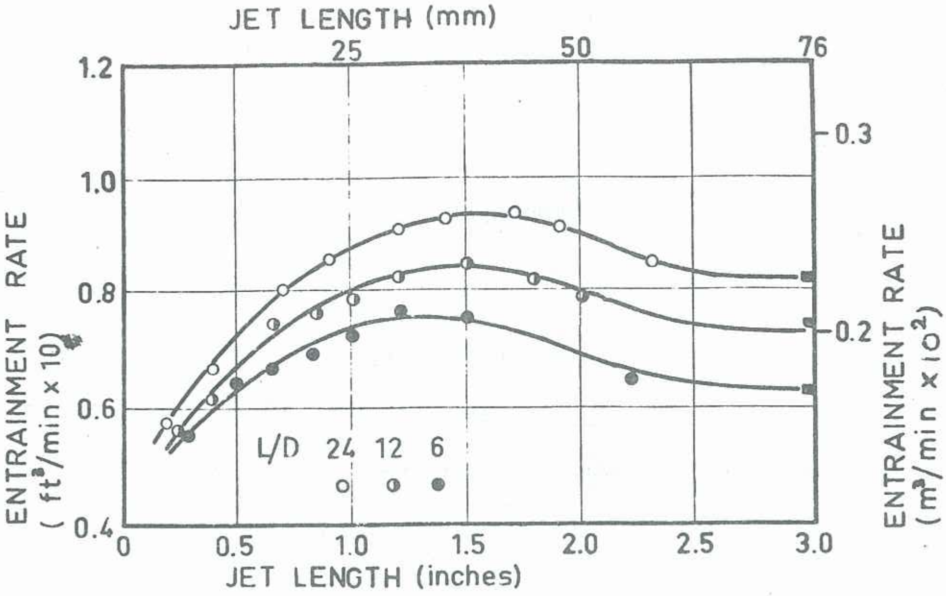

FIGURE 3

PIPE DIAMETER	0.993 in (25.2 mm)
NOZZLE DIAMETER	0.254 in (6.45mm)
JET VELOCITY	37.5 ft/sec (11.4 m/s)
JET REYNOLDS NUMBER	74 000
PIPE REYNOLDS NUMBER	19 000

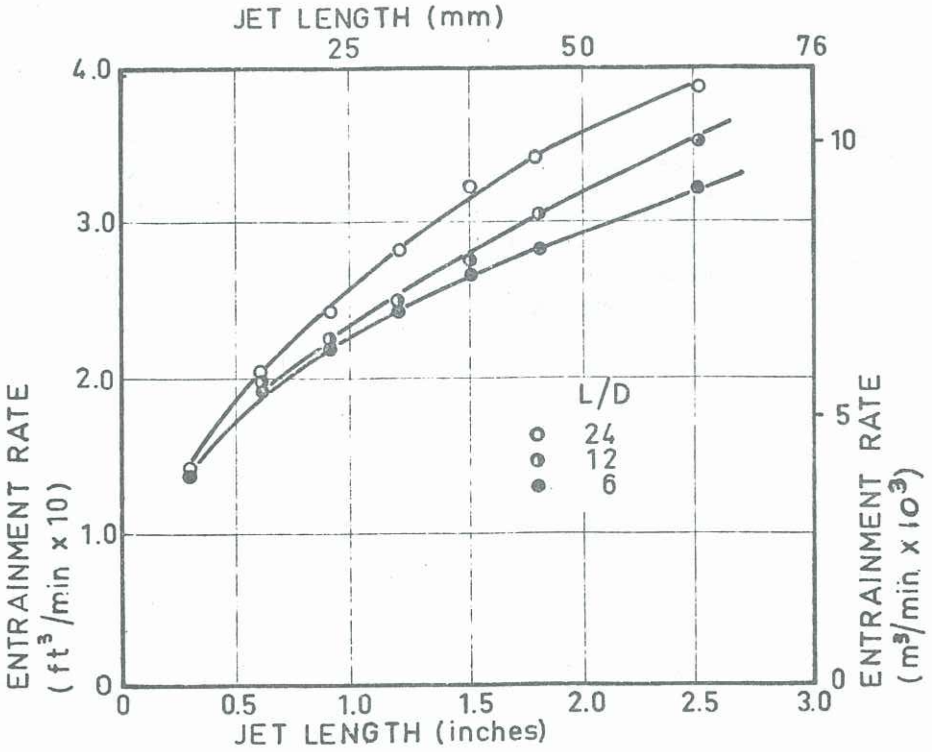

FIGURE 5

PIPE DIAMETER	0.993in (25.3 mm)
NOZZLE DIAMETER	0.254in (6.45mm)
JET VELOCITY	60.0 ft/sec (18.3m/s)
JET REYNOLDS NUMBER	118 000
PIPE REYNOLDS NUMBER	30 200