WATER ENTRAINMENT INTO UNDERWATER THERMAL PLASMAS

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ABSTRACT

Water entrainment into gas jets from underwater plasma torches has been measured. Variables include gas flow rate, nozzle diameter and gas injection pattern. Water can be entrained at rates to over 20 times the gas mass flow rate within only 10 nozzle diameters distance. Implications for entrainment into a plasma jet, even at lower rates, are discussed. Length of the underwater gas jets indicates that water entrainment is a major factor governing the termination of gas or plasma jets underwater.

1.   INTRODUCTION

Thermal plasmas operating underwater are used extensively for plasma cutting of metals and other materials. A more recent development has been underwater plasma spraying for deposition of protective coatings [1,2] In both applications the surrounding water can act beneficially by trapping fume and other particulates, excluding air, restricting heat dissipatation in the workpiece or substrate and absorbing acoustic and optical radiation. Although air is excluded there is obviously the potential for water to interact with the plasma and plasma/surface impingement zone. This could for example change the temperature and velocity fields and the chemical composition of the plasma. In a previous report [3] the formation of hydrogen and oxygen in underwater plasma cutting was quantified. One of the mechanisms suggested then as promoting formation of hydrogen and oxygen was entrainment of water into the plasma followed by thermal dissociation. Recently Verstak et al [4] in analysing aspects of underwater plasma spraying have argued that water entrainment into the plasma jet can be neglected. The present paper describes measurement and modelling of water entrainment into underwater gas jets and the potential implications for underwater plasmas. A detailed analysis of water interactions in underwater plasma spraying is presented in another session [5].

2. EXPERIMENTAL

The technique used to measure water entrainment and jet angles is a development [6] of that used by Bell et al [7] and by Kennedy and Collier [8]. They studied horizontal jets of nitrogen formed at relatively small nozzles with high differential pressures. Here downward flowing jets from nozzles typical of those used in plasma cutting and spraying were studied. The plasma torch is mounted in a transparent rectangular tank divided into two compartments (Fig 1). In the dividing wall a machined orifice is fitted in line with the torch nozzle. Vertical distance between the nozzle and orifice, x, can be set accurately and the orifice diameter varied by changing the orifice. In operation the torch discharge stream passes through the orifice and any entrained water is carried into the second compartment. The rate of water entrainment is then obtained directly from the rate at which water overflows from the second compartment. A continuous water feed to the first compartment and an overflow ensure a constant and equal level in the first compartment. The angle of the diverging jet is obtained by adjusting x until the orifice just skims gas from the periphery of the jet.

3. EXPERIMENTAL RESULTS

The variation in water entrainment with axial distance for cold jets of argon gas from a 1.6mm diameter nozzle is shown in Figure 2. Entrainment is clearly substantial, reaching over 15 times the mass flow rate of argon . Swirl as used in some plasma torches increases the rate of water entrainment, the rate increasing with angle of swirl. Swirl also increased the jet angle over that for axial injection. Total included angles were 33° for axial flow and 49° and 58° respectively for 60° and 80° swirl. Because of the increased entrainment rate swirling jets broke up within a shorter axial distance than axial jets (Figs 2 and 3). Increasing the argon flowrate increased overall jet length (Fig 3). Whilst the absolute rate of entrainment also increased with gas flow rate beyond about 4mm, the water/argon mass ratio declined. This decline in water concentration with gas flow rate was also seen with another design of nozzle of diameter 1.4mm (Fig 4) using axial injection (Torch B). There even higher water/gas ratios, up to 24, were recorded. The drop in entrainment at X above 7.2 indicate jet breakup there. Gas flowrate had less effect on entrainment with a 1.85mm diameter nozzle of the same design (Torch B) except towards the end of the jet where the water/gas ratio increased with gas flow rate (Fig 5). This latter trend also occurred with an 8mm diameter nozzle in axial flow. Entrainment rates were substantially lower for that larger nozzle but the resulting water/gas ratio still reached nearly 2 within only 1.5 nozzle diameters downstream. With this size of nozzle at gas mass flow rates of the order used in underwater plasma spraying the jets are less coherent and break up relatively near to the nozzle. Buoyancy effects are more significant.

All results reported here apply to gas jets at ambient temperatures. In the next stage of the investigation non-transferred plasmas will be studied.

4. DISCUSSION

The results show many of the characteristics of entrainment into turbulent jets, especially the very rapid increase in total mass flow with distance resulting from momentum transfer. Increased entrainment rate and jet angle with swirl are also characteristic of turbulent jets.

Quantitative comparison with other data is difficult as there appears to have been few studies of turbulent gas jets in liquids. The very large majority of reports and correlations on turbulent jets deal with single phase systems, either gas or liquid. Also most have concentrated on the fully developed turbulent jet region some 10 or more nozzle diameters downstream whereas here we are interested also in the region closer to the nozzle.

Equation 1 of Ricou and Spalding [9] is often used for prediction of entrainment into fully developed single phase jets with $C = 0.32$

$$m_e/m_o = C(x/d_o)(\rho_e/\rho_o)^{1/2}. \quad \dots\dots\dots(1)$$

Entrainment nearer the nozzle is lower than predicted by equation (1). Hill [10] obtained a relationship between C and axial distance from gas/gas entrainment measured at x/d_o down to 1.0. Equation (1) was implied as being valid irrespective of the density ratio ρ_e/ρ_o but that was apparently based on measurements in gas/gas and liquid/liquid systems. For gas or plasma in water, $(\rho_e/\rho_o)^{1/2}$ can exceed 25 as compared to near unity in single phase systems.

Measured entrainment for 1.4mm and 8.0mm nozzles and predictions by equation (1) using Hill's values of C are compared in Table 1. These agree reasonably well near the nozzle but this may be fortuitous as equation 1 grossly overpredicts entrainment further down the jet.

Table 1. Comparison of measured and predicted entrainment

x/d_o	1.40mm Predicted/Measured		x/d_o	8.0mm Predicted/Measured	
1.52	0.78	1.08	0.78	0.80	0.68
2.31	1.22	1.61	1.23	0.76	1.03
4.66	1.99	2.23	1.71	1.25	1.40
7.23	2.57	3.47			
7.76	3.53	4.37			
Air mass flow, kg/s x 10^{-3}	0.69	1.44		1.74	2.0

Measurements have still to be made on non-transferred plasma jets but there seems no fundamental reason why such a jet should not also entrain water. This could be in liquid form and/or as steam. For an 8mm nozzle typical of plasma spraying the Reynolds number for an argon plasma at the nozzle is calculated as being of the order 500-4000 depending on temperature at which viscosity is taken and mass flow rate. Turbulent jets can be formed at lower Re than for the onset of turbulence in pipe flow. Also for a non-transferred plasma jet, arc root movement in the nozzle would be expected to promote turbulence.

Some evidence of a link between entrainment in cold gas jets and interactions between plasma and water was obtained by Ryan [6,3]. The rate of hydrogen formation from an underwater plasma increased with swirl, analogous to the increase in water entrainment in cold gas experiments with the same torch. Greater entrainment and thermal dissociation of water was proposed as one reason for the rise in hydrogen formation. A rise in hydrogen formation caused by impinging a non-transferred argon plasma onto an inert plate suggested that more intensive mixing of water with the plasma promoted hydrogen formation. The equilibrium yields of hydrogen from dissociation of water depend on temperature and on the concentration of water in the water/argon mixture [6]. As temperature and water/argon ratio change along the jet the prediction even of thermodynamic equilibrium yields is complex. Previous yields of hydrogen (6,3), if produced only by dissociation, were equivalent to about 6% wt water on argon i.e. a small proportion of measured entrainment.

The observed lengths of the underwater gas jets in present experiments are relevant to the question of the limiting water depth for plasma spraying. Verstak et al [4] proposed that an underwater plasma jet would stop when $\rho u^2/2 < \rho_w g h_w$. $\rho u^2/2$ is a velocity head pressure for the plasma and h_w the 'dive' depth or torch immersion depth.

Present cold gas jets persist only to lengths of the order 10-30mm in water depths of about 200mm. As the velocity head pressures calculated from flow rate and known temperature are equivalent to water depths of several metres then clearly there is some other mechanism involved. Here it is entrainment of water which effectively quenches the cold jet within a relatively short distance. This mechanism was also proposed earlier [1] as the reason for the need for shorter stand-off distances in underwater plasma spraying, entrained water acting both to slow down the plasma and reduce its temperature in evaporating.

5.   CONCLUSIONS

Cold gas jets from underwater plasma torches can entrain water at rates to over 20 times the jet gas mass flow rate within about 10 nozzle diameters axial distance. Swirling the torch gas increases entrainment and jet angle. Only a fraction of the entrainment measured in cold gas jets would influence the velocity and temperature fields and composition of a plasma jet. The observed lengths of the gas jets underwater show that termination of the jet occurs more readily than predicted

by a criterion based on velocity head pressure considerations. Water entrainment is suggested here as a more dominant mechanism.

ACKNOWLEDGEMENTS

SYMBOLS

C	Factor on equation 1	ρ	Density of plasma or gas
d_o	Nozzle diameter	ρ_e	Density of entrained fluid
g	Gravitational acceleration	ρ_w	Density of water
h_w	Water depth	Re	Reynolds No
m_e	Mass flow rate of entrained fluid	u	Velocity
m_o	Mass flow rate of nozzle fluid	x	Axial distance downstream of nozzle exit
m_w	Mass flow rate of water	X	x/d_o
m_a	Mass flow rate of air or argon		

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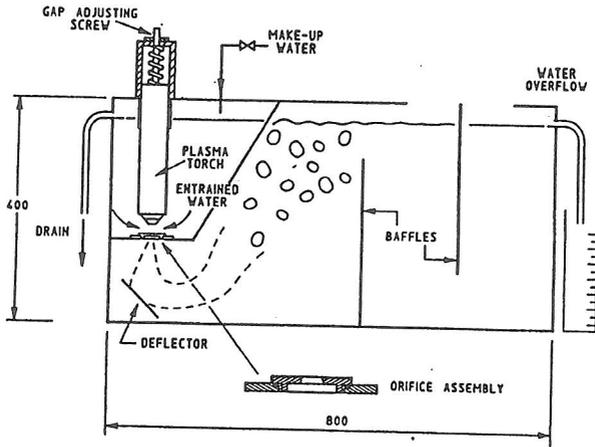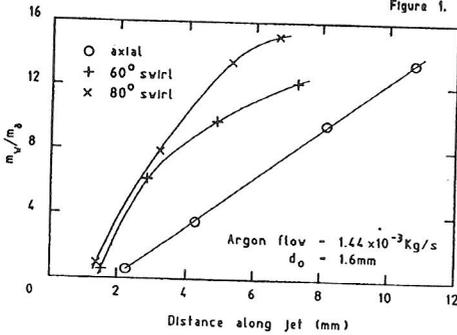
Figure 1. EXPERIMENTAL RIG

Figure 2. RATIO OF WATER ENTRAINMENT RATE TO ARGON FLOWRATE IN AXIAL AND SWIRLING JETS (TORCH A).
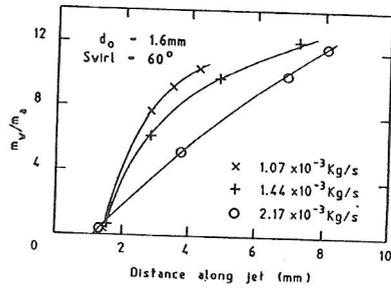

Figure 3. EFFECT OF ARGON FLOWRATE ON ENTRAINED WATER CONCENTRATION IN SWIRLING JETS (TORCH A).
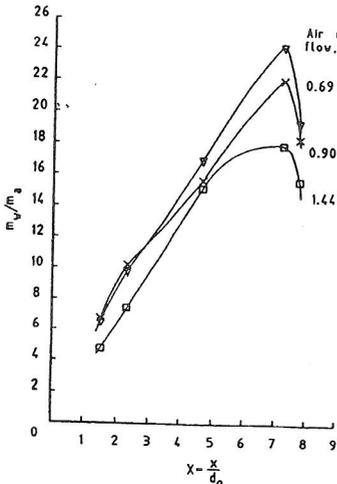

Figure 4. EFFECTS OF AIR FLOW RATE AND AXIAL POSITION ON WATER ENTRAINMENT FOR 1.4mm NOZZLE IN TORCH B (AXIAL FEED).
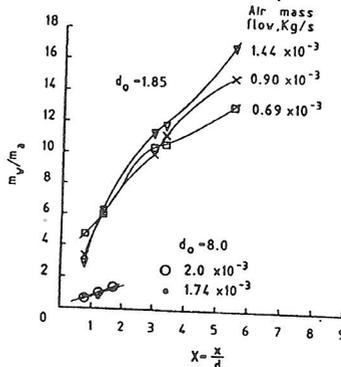

Figure 5. EFFECTS OF AIR FLOW RATE AND AXIAL POSITION ON WATER ENTRAINMENT FOR 1.85mm AND 8.0mm NOZZLES IN TORCH B (AXIAL FEED)