Mechanisms of Power Dissipation in the Column of High Pressure Argon-Tungsten Arcs

Models are developed that predict the influence of main arcing variables on power dissipation over pressures ranging from 1 to 42 bars, or 1 to 41 atmospheres

BY C. J. ALLUM

ABSTRACT. Manual hyperbaric welding may now be regarded as a well established subsea repair and maintenance technique to water depths of at least 200 meters (~650 ft). Manned trials do, however, indicate (Ref. 1) that physiological limitations will prohibit the fully manual use of this technique beyond about 400 meters (~1300 ft). For such applications it appears presently that the role of the welder-diver will have to be supplemented by a degree of process automation. These developments will require a greater appreciation of process behavior than has hitherto been necessary.

In this paper, simple models are developed with the aim of understanding the influence of the main arc variables (with emphasis on ambient pressure) on power dissipation in a gas tungsten arc. Predictions are compared with experimental findings obtained by operating such arcs in pressure chambers over the range 1-42 bars, i.e., appoximately 1 to 41 atmospheres.*

Introduction

Argon-tungsten arcs have long been used as heat sources for welding under normal ambient conditions. During the past ten years such arcs have also been used for underwater welding tasks. In this application the arc is usually operated in a dry high pressure (equivalent to water depth) environment constructed around the region to be welded.

The nature of the arc heat source and the suitability for use in welding is significantly influenced by ambient pressure. The influence of pressure on the characteristics of the column of such a heat source forms the basis of the present paper.

The most obvious influences of pressure are on arc appearance and operating voltage. It is generally observed that the column contracts and appears more luminous while voltage increases. These changes clearly mirror pressure-dependent energy exchanges. Experimental results presented here give details of the pressure dependence of arc voltage and radiative output, and a simple model is developed to explain many of these observations. Abbreviations and symbols for the terms used to describe the model during its development are defined in Table 1.

Experimental Results

Experiments have been performed in pressure chambers, such as shown in Fig. 1, over the range 1 to 42 bars. The principle arc form investigated was the free-burning gas tungsten arc in argon and helium environments. Such arcs were run on steel anodes (stationary and moving) and cooled-copper anodes.

Typical voltage characteristics obtained during these experiments are shown in Figs. 2 and 3. It can be seen that arc voltage (V) increases with pressure. However, the increase is such that the extrapolated zero arc length voltage (V_o) is largely independent of pressure. Changes in arc voltage are, therefore, due to pressure dependent phenomena in the column (voltage contribution, V_c). V_o is also little influenced by arc current (at least for the 150 A $\geq$ I $\geq$ 75 A investigated).

Figure 3 shows that V_o may be given by 9 – 10 V for an argon-copper, gas-work piece combination. Other combinations not shown here (Ref. 2) give 8 ± 1 V for Ar-Fe, ~ 10 V for He-Fe and ~ 15 V for He-Cu. It can also be seen from Fig. 3 that arc voltage has a substantially linear dependence on arc length (l) for short arcs. Thus $V_c \simeq El$ where E is defined by the short arc gradient of the V-l characteristic. Values of E obtained in this manner are shown in Fig. 4 for I = 100 A. It can be seen that E may be quite well represented by a square root of pressure law for all arc conditions considered. The nature of the V-I characteristic (Fig. 2) is such that E is not very

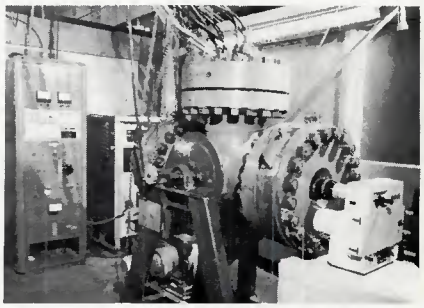

Fig. 1 – Pressure chamber (operating range: 1-135 bars)

*1bar = 0.987 atmosphere (atm).

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Table 1—Abbreviations with Definitions

I	Arc Current
V	Total Voltage
V_o	Zero arc length voltage
V_c	Column Voltage Contribution
E	Electric field strength (V/mm)
l	Arc length (mm)
P	Ambient pressure (bars)
Q	Total Power loss from column (Watts)
Q(cv)	Convective Power loss from column (Watts)
Q(R)	Radiated Power loss from column (Watts)
$Q(\kappa)$	Conductive Power loss from column (Watts)
h	Enthalpy
σ	Electrical Conductivity
κ	Thermal Conductivity
ΔT	Average temperature difference between arc axis and boundary (k)
ρ	Plasma density
ρ_1	Plasma density at 1 bar
ρ_∞	Density of cool surrounding atmosphere
$\rho_\infty 1$	Density of cool surrounding atmosphere at 1 bar
q(T)	Average column radiative source strength (Watts/m^3)
g	Acceleration due to gravity
μ_o	Permeability of free space
r	Arc radius at cathode
R	Arc radius near anode
$\tau(= A \cdot l \cdot d)$	Arc volume
$A(=\pi R^2)$	Arc cross-sectional area near anode
d	Dimensionless geometric factor
$J\left(=\frac{I}{A}\right)$	Arc current density
B	Magnetic field strength
u	Plasma flow velocity
$\bar{u}$	Radially average plasma flow velocity (m/s)
$\bar{u}_m$	Value of $\bar{u}$ when magnetic forces dominate
$\bar{u}_B$	Value of $\bar{u}$ when buoyancy forces dominate
F	Axial force (units of N)
F_m	Axial force (magnetic) (units of N)
F_B	Axial force (Buoyancy) (units of N)
ln	Natural logarithm
$f = ln(R/r)$	
P_s	Stagnation pressure at anode (N/m^2)
R_e	Reynolds number of plasma flow
Φ, $\bar{\Phi}$, $\bar{\Phi}(cv)_m$, $\bar{\Phi}(cv)_b$	Thermodynamic functions defined in text
α, β, γ, a, b, c, m, n	Dimensionless constants

sensitive to changes in arc current but is expected to increase slightly with I at high pressures.

The above results, coupled to the observed decrease in column diameter (Ref. 3), indicate a very strong increase in arc power density ($J \cdot E$). Arc diameter has been observed (Ref. 3) to decrease as $P^{-0.17}$ (for $14 \geq P \geq 1$) or as $P^{-0.25}$ in a strong shielding gas flow. The increase in average arc power density is, therefore, between $P^{0.84}$ and P. These values also indicate that electrical conductivity is largely unaffected by pressure, *i.e.*, by Ohms law $J = \sigma E$ where the pressure dependence of J is similar to that of E and hence arc electrical conductivity (σ) is little influenced by pressure.

The V-I characteristic has a negative gradient below some critical current in argon. Above this current (50 ~ 100A) the V-I curve has a positive slope. Helium arcs behave in a markedly different manner, exhibiting no positive characteristic (Fig. 5) at any pressure examined (at least to currents of 150A). This behavior is discussed in the following section.

A characteristic of atmospheric GTA welding arcs is that power generation is largely confined to the electrode regions, *i.e.*, $V_o > V_c$. This is no longer true (Fig. 3) for many hyperbaric welding situations; consequently, the column is expected to play a larger role in determining fusion characteristics. It is, therefore, considered important to gain an insight into the influence of pressure on power generation in the arc.

Voltage characteristics reported above are the result of conductive $Q(\kappa)$, convective Q(CV) and radiative Q(R) energy exchanges, *i.e.*,

$$I \cdot V_c \simeq Q(CV) + Q(\kappa) + Q(R) \equiv Q \qquad (1)$$

Direct measurements of Q(CV) and $Q(\kappa)$ are not possible, but estimates may be made from flow and temperature field data. Q(R) is the most difficult factor to consider theoretically but is amenable to direct measurement. An estimate of the total radiative power leaving the column has been found using a device described elsewhere (Ref. 2). After correcting for radiation from the electrode regions and background effects, the results shown in Table 2 were obtained.

Each result shown in Table 2 is the average of 4 values corresponding to arc lengths of between 2 and 8 mm (0.08 and 0.31 in.). These must be regarded as minimum values as absorption in the argon gas between the arc and receiver has been neglected. Also, the lamp blacked absorbing surface was assumed to have a flat spectral response with an absorbtivity of 0.9. It can be seen that, for argon, Q(R) is about 18% of Q at 1 bar and 25% at 42 bars, although the respective fractions of the total process power are much smaller (typically 5% at 1 bar).

Clearly radiation is a significant transfer mechanism in the arc column and becomes increasingly more so with pressure. It is also interesting to note that no significant difference exists in the radiative behavior of 75 and 125 A arcs. However, the 50 A arc is a proportionally weaker radiater. It can be seen from Table 2 that the radiative output has a slightly stronger pressure dependence

Table 2—Percentage of Arc Column Power Radiated from an Argon Column (Bracketed Percentages for Helium), %

Pressure, bars	Radiated arc column power for indicated arc currents, %				
	For 50 A	For 75 A	For 100 A	For 125 A	Average[a]
1	13.4	17.6	19.2 (6.1)	18.0	18.3 (6.1)
7.8	14.6	21.9	17.3 (8.3)	19.5	19.6 (8.3)
21.4	19.3	25.6	26.9	22.5	25.0
41.2	18.9	26.9	23.0	24.9	25.0

(a) 50 A results not included in averages.

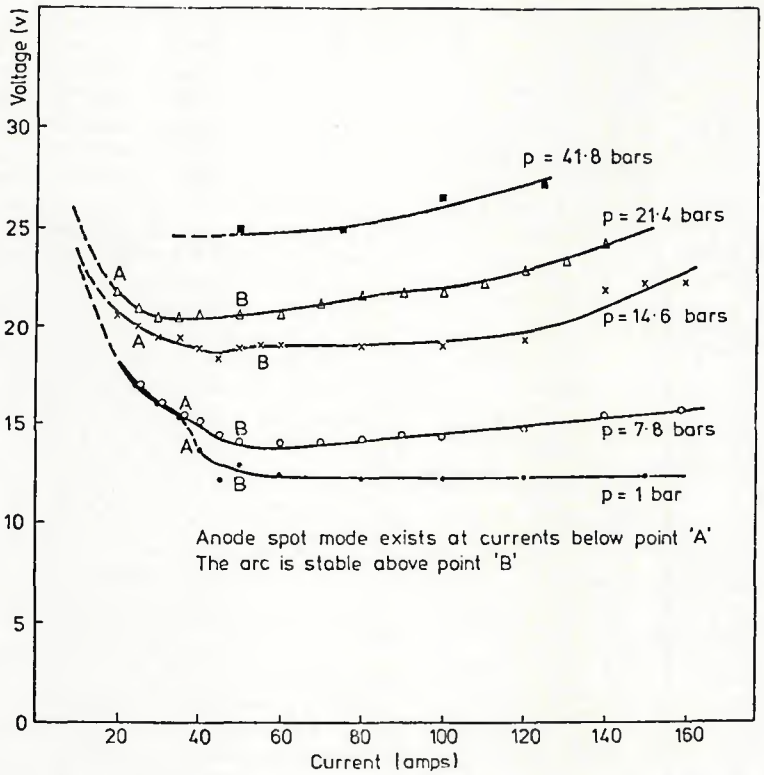

Fig. 2 — V-I characteristics of a 4 mm (0.16 in.) long arc on a moving steel anode (flat position)

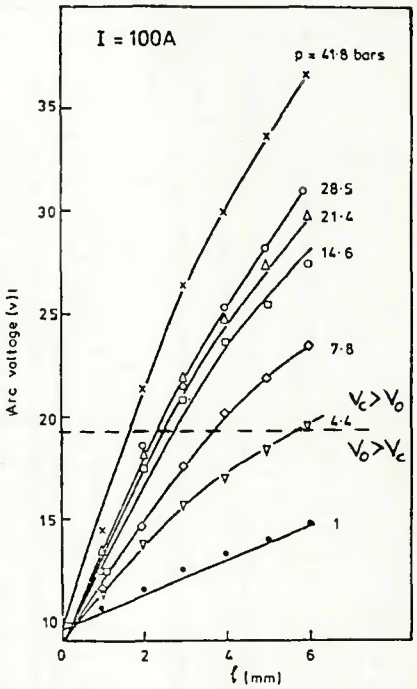

Fig. 3 — Voltage dependence on arc length (l). GTA arc with argon shielding above a cooled copper anode

than E, but for the present purposes the data are expressed as

$$Q(R) = (0.22 \pm 0.04)\, I \cdot E \cdot l, \quad \textit{i.e.,}\ 22 \pm 4\% \text{ of } Q \qquad (2)$$

For helium arcs a much smaller fraction leaves the arc as radiation.

Discussion

An attempt is made to understand the voltage dependence on pressure, arc length and current by the use of a simple model describing the components of Q.

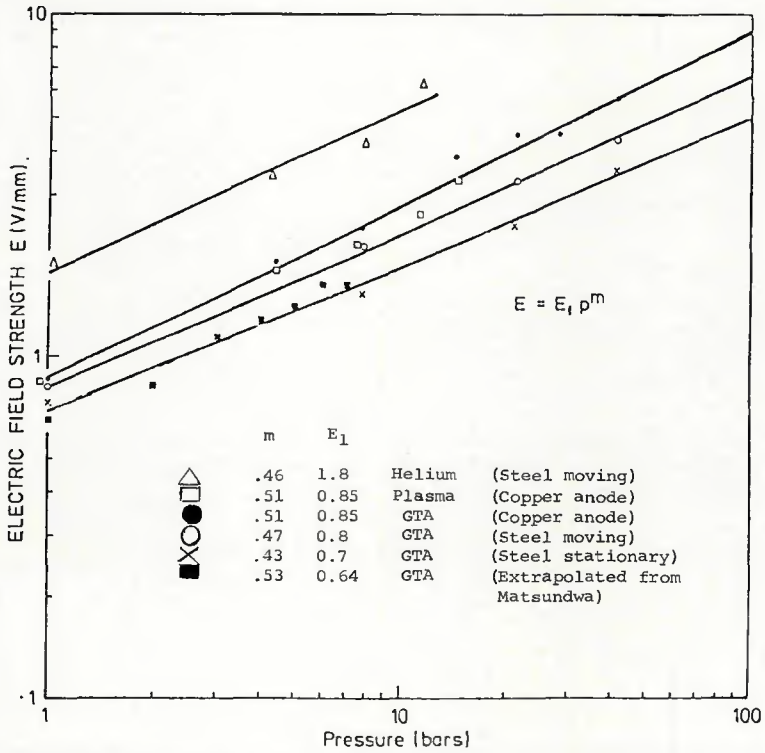

Fig. 4 — Electric field strength for a range of arc conditions

This model assumes that temperature conditions within the column are little influenced by pressure and that enthalpy (h) as well as the electrical (σ) and thermal (κ) conductivities are pressure insensitive.

For many purposes these assumptions are not unrealistic over the temperature range encountered in GTA arcs. (The pressure insensitivity of σ and κ for argon near 12,000 K or 22,000°F is somewhat surprising. However, such results have been obtained by Devoto (Ref. 4), and more recently by Kannappan and Bose — (Ref. 12). The pressure dependence is then almost entirely density (ρ) dependent. Convective dissipation can be written as

$$Q(CV) \simeq \rho \cdot A \cdot \bar{u} \qquad (3)$$

where $\bar{u}$ is the average axial velocity across an area A ($=\pi R^2$) near the anode. $\bar{u}$ may be estimated from momentum flux (F) considerations. The behavior of $\bar{u}$ depends on the mechanism of momentum generation. If convection is generated by a $J \wedge B$ interaction, then:

$$F_m = \int_0^\infty \rho u^2 dA \approx \frac{\mu_0 I^2}{4\pi} \cdot \ln \frac{R}{r} \qquad (4)$$

where r is the arc radius near the cathode. This enables a root mean square velocity u(rms) to be defined. Equating this to the mean value $\bar{u}$ gives

$$\bar{u} = \sqrt{\frac{\mu_0 I^2 f}{4\pi\rho A}} \qquad (5)$$

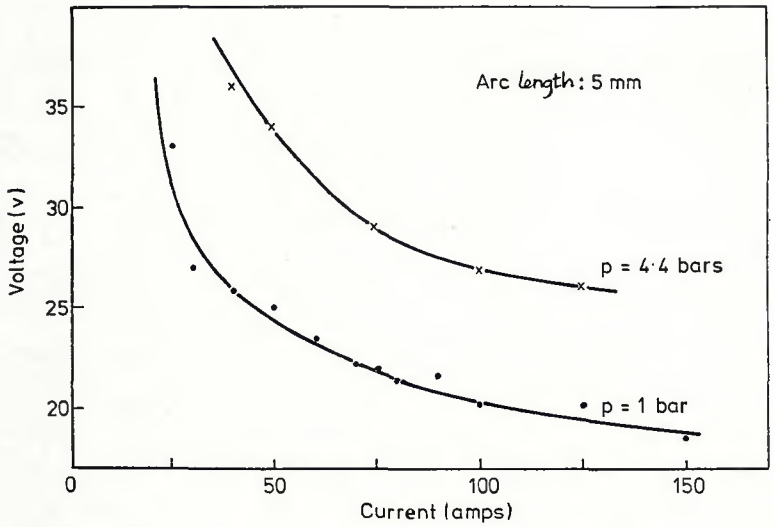

Fig. 5 — V-I characteristic for a 5 mm (0.20 in.) long GTA arc with helium shielding on a steel anode

(where $f = /nR/r$).

It should be noted that this definition of $\bar{u}$ is not affected by viscous forces and is exact within the limitations of identifying $\bar{u}$ with u(rms) and the implicit isothermal assumption. Equation (3) may now be written as:

$$Q(CV) = \frac{h \cdot I \cdot R}{2}\sqrt{\mu_o \rho f} \qquad (6)$$

Buoyancy is the dominant force in a vertical arc when $\rho_\infty g \cdot A \cdot l > F_m$. Buoyancy is also the dominant force possibly for much less stringent conditions, *i.e.*, it may be dominant in the outer reaches of the column for less stringent conditions and thereby affects behavior on the axis (Ref. 5). This inequality may be satisfied for very high pressure (Ref. 5), long arcs or low currents. Under these circumstances:

$$\bar{u} \simeq \sqrt{\frac{\rho_\infty g \cdot l}{\rho}} \qquad (7)$$

where ρ_∞ is the density of the cool surrounding atmosphere and g is the acceleration due to gravity.

It is interesting to note that in buoyancy dominated arcs $\bar{u}$ is insensitive to pressure. This compares with a predicted decrease in $\bar{u}$ when magnetic momentum generation dominates despite column contraction — equation (5). Buoyancy based estimates, therefore, give the minimum plasma flow speeds that might be expected at ultra high pressures (*i.e.*, a few m/s). (The pressure dependence of other physical properties, based on equations introduced here, are given in the Appendix.) Convection is then described by:

$$Q(CV) \simeq \pi \cdot h \cdot R^2\sqrt{\rho_\infty \cdot \rho \cdot g \cdot l} \qquad (8)$$

Additional expressions are required for arcs in cross-flows (Ref. 6) or where swirl exists.

An estimate of $Q(\kappa)$ may be obtained in an approximate manner from:

$$Q(\kappa) = 2\pi\kappa \cdot \Delta T \cdot l \qquad (9)$$

where end effects are neglected and ΔT is the temperature difference between arc axis and surface (assumed linear). For parabolic temperature profiles $Q(\kappa)$ is readily shown to be twice the value. However, this is not important to the present argument, because only qualitative predictions are made.

The most difficult behavior to justify with a simplistic description is net radiation from the column. As a first approximation it is assumed that radiative processes increase in proportion to the number of radiating particles. Referring to the literature (Ref. 7), it is also assumed that radiation leaving the arc increases in a similar manner:

$$Q(R) = P \cdot \tau \cdot \overline{q(T)} \qquad (10)$$

where $\overline{q(T)}$ is some function of temperature (Refs. 7 and 8) averaged over the temperature field of the arc volume (τ) and P the absolute pressure in bars.

These equations may be combined to give:

$$I \cdot V_c = \rho h A \bar{u} + 2\pi K \cdot \Delta T \cdot l + P \cdot \tau \cdot \overline{q(T)} \qquad (11)$$

where $\bar{u}$ depends on the mechanism of momentum generation. V_c may be related to the relevant variables by Ohm's law:

$$V_c = I\, l/\sigma \cdot A$$

Combining these expressions gives an equation that may be regarded as a fourth order in R. For the present purposes it is sufficient to examine the general behavior of R when one mechanism dominates. The form of the equations is such that it is then possible to obtain relationships of the type:

$$R = \Phi I^a \cdot l^b \cdot P^c \text{ and } V_c = \Phi I^\alpha \cdot l^\beta \cdot P^\gamma \qquad (12)$$

where Φ and $\bar{\Phi}$ are principally thermodynamic functions and a, b, c, α, β, γ, are given in Table 3.

The predicted pressure dependence of these models is remarkably similar (with the exception of the purely conductive arc), *i.e.*, the pressure dependence of column voltage is between 0.33 and 0.50 which is in fair agreement with the observed pressure dependence of E. Similarly, the column contracts from −0.17 to −0.25 which is precisely the range observed in practice. On this basis it is difficult to distinguish the dominant mechanisms in high pressure arcs.

Solutions that simultaneously take into account all such mechanisms are expected to produce a similar dependence on pressure as given above. It is also worth noting that the predicted radiative dependence is close to that measured experimentally despite the simplistic

Table 3—Dependence of Arc Voltage and Radius on Arcing Parameters for Different Arc Models

		R			V_c		
	Φ	a	b	c	α	β	γ
CM (magnetic)	$\Phi(CV)m$	+0.33	+0.33[a]	−0.17	+0.33	+0.33[a]	+0.33
CV (buoyancy)	$\Phi(CV)b$	+0.50	+0.13	−0.25	0.00	+0.75	+0.50
R	$\Phi(R)$	+0.50	0.00	−0.25	0.00	+1.00	+0.50
K	$\Phi(K)$	+1.00	0.00	0.00	−1.00	+1.00	+0.00

(a) Valid only for arcs long enough such that 'f' changes slowly with:

$\bar{\Phi} \cdot \Phi^2 \pi\sigma = 1$

$\Phi(CV)m = \left(\frac{f \cdot \rho \cdot \mu_o \cdot h^2}{4\pi\sigma}\right)^{1/2}$

$\Phi(CV)b = \left(\frac{h^2 \rho_\infty' \cdot \rho' \cdot g}{\sigma^2}\right)^{1/4}$

$\Phi(R) = \left(\frac{\bar{q} \cdot d}{\sigma}\right)^{1/2}$

$\Phi(K) = 2\pi K \Delta T$

where d is a geometrical factor (*e.g.*, 1 for a cylindrical column) ρ, is the column density at 1 bar and ρ_∞, the cool ambient gas density 1 bar.

Table 4—Tabulated Pressure Dependence of Arc Properties

Property	Symbol	Source	Exponent x	Value of x when n = 0.2 (see Theory and Experiment)
Arc radius	R	P^{-n}	−n	−0.2
Current density	J	$J\alpha R^{-2}$	+2n	+0.4
Electric field strength	E	$E\alpha J$	+2n	+0.4
Mean flow velocity (magnetic)	$\bar{V}_m$	Eq 5	n-½	−0.3
Mean flow velocity (buoyancy)	$\bar{V}_B$	Eq 7	0	0.0
Reynolds number (plasma, magnetic)	Re	Ref.[5]	½	+0.5
Axial force (magnetic)	F_m	Eq 4	0	0.0
Axial force (Buoyancy)	F_B	see text	1-2n	+0.6
Stagnation pressure at anode (magnetic)	P_s	$P_s\alpha \cdot \rho \cdot \mu^2$	2n	+0.4
Column radiative loss	Q(R)	Eq 10	1-2n	+0.6
Column conductive loss[(a)]	Q(K)	Eq 9	0	0.0
Column convective loss (magnetic)	Q(CV)m	Eq 6	½-n	+0.3
Column convective loss (buoyancy)	Q(CV)b	Eq 8	1-2n	+0.6

(a) x will be positive if turbulence significantly affects K.

treatment given to this problem.

A firmer indication of the relative importance of the various mechanisms is given by the nature of the V-I characteristic. Only in convective arcs is a rising characteristic predicted. Indeed, weakly rising characteristics are often observed for argon arcs—Fig. 2. This explains why the effect of pressure on V diminishes as arc current is reduced, *i.e.*, the conductive term diminishes.

Helium arcs exhibit negative characteristics indicating conductive behavior. Such behavior is complicated by the emergence of a powerful arc jet with increasing pressure (Ref. 9), thereby enhancing the pressure dependence of arc voltage. However, the low density and high thermal conductivity of helium ensures that conduction remains dominant—see equations (6) and (9).

The influence of turbulence may be incorporated by using suitable values for κ. κ is known to increase dramatically under such conditions (Ref. 10). This appears to be required at high pressures if the observed dependence of arc voltage on shielding gas flow rate (Ref. 9) is to be explained. Further to this, the column is predicted to contract in turbulent flows, *i.e.*, $R\alpha\Phi\alpha\ \kappa^{-0.5}$. This gives an explanation of the shielding gas flow dependence of arc radius observed experimentally.

It may be seen from Table 3 that only convective arcs diverge significantly between anode and cathode. Expansion is associated with entrainment and is strongest in $J \wedge B$ dominated columns. Table 3 also shows that radiative and conductive arcs are expected to have more or less linear arc voltage-arc length dependencies. Such a result is in agreement with the highly linear dependence of V observed in helium based (40l/min or 84 cfh He and 10l/min or 21 cfh Ar) arcs—even at long arc lengths (Ref. 11).

Conclusions

The simple model developed here throws some light on the observed pressure dependence of arc characteristics. In particular it is shown that argon GTAW arcs undergo a slow transition from $J \wedge B$ convectively dominated at 1 bar to being strongly influenced by other factors (buoyancy, radiation, turbulence) at very high pressures. Similarly, helium arcs become increasingly influenced by convection with pressure, thereby explaining the observed pressure dependence of arc voltage.

Acknowledgment

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Appendix

Simple expressions introduced in the text may be used to indicate the influence of pressure on a range of arc properties. This is possible only because of the simple manner in which pressure dependence can be separated from other effects, *i.e.*, it is generally possible to express this by a simple power law scaling factor of the form p^x. Values of x are given in Table 4 in terms of n where arc radius (R) is proportional to P^{-n}.

A full discussion of these results is not given here. However, it is interesting to note some implications for weld pool behavior. The increase in stagnation pressure, despite the insensitivity of arc force, should result in significantly greater pool depressions. Also, the increase in column Reynolds number should lead to enhanced heat transfer from the column to the pool. Weld pool geometry is also likely to change as a result of an increase in current density, *i.e.*, indigenous $J \wedge B$ weld pool flow will be stronger and the arc will be a more point-like heat source.

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