AIR ARCS BURNING IN TURBULENT ROUND JET

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ABSTRACT

Computational results for DC air arcs burning in a turbulent round jet are reported and compared with experimental results. It has been found that turbulent energy transport inside the high temperature arc core is not important. The interaction between the arc and the jet generates pressure waves resulting in arc voltage oscillating with a period of approximately 0.5 ms. The amplitude of such voltage oscillation depends on current and the width of the jet.

1. INTRODUCTION

There has recently been much interest in the search of arcing gas other than SF_6 due to a desire of reducing the use of greenhouse gases for environment protection. Air gas blast breakers were widely used before the introduction of SF_6 breakers. At that time there was a lack in our understanding of detailed physical processes occurring in air arcs, especially regarding radiation transport. With the advancement of computer technology and of our understanding of arc physics there is a renewed interest to study the interaction between an air arc and its surrounding flow in the hope to find the physical mechanisms responsible for arc quenching.

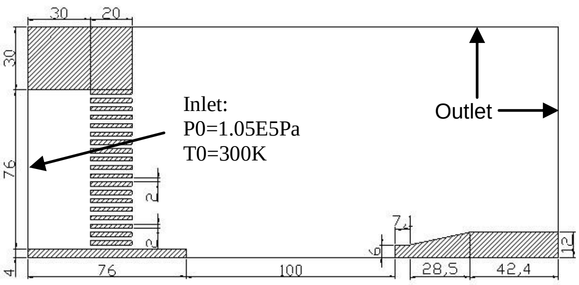
The present investigation forms part of a programme concerning the replacement of SF_6 as a medium for arc interruption. Turbulence plays a critical role in extinguishing the arc in SF_6 [1]. However, for nitrogen nozzle arcs, prediction based on laminar theory agrees well with experimental results [2]. In order to ascertain the role of turbulence in the determination of arc characteristics in air we simulate the experimental situation of [3] where an air arc burns in a turbulent round jet with an inlet Mach number of 0.2 or 0.8 (Fig. 1) and at a DC current of 5 kA or 10 kA.

2. ARC-FLOW MODEL, RADIATION, COMPUTATAIONAL DOMAIN AND BOUNDARY CONDITIONS

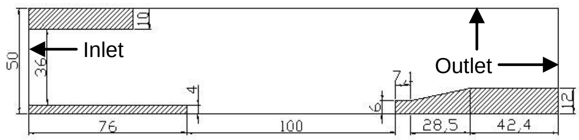
The arc and its surrounding jet are assumed in LTE. The time averaged conservation equations are the same as those in [4] and the standard k-epsilon model is adopted to model the turbulent effects. Current continuity equation is used to compute the electrical field. Arc motion is mainly driven by the Lorentz force generated by the interaction of arc current with its own magnetic field. Electrical conductivity, equation of state and other thermodynamic quantities and transport coefficients are taken from Yos [5].

Radiation transport is of extreme importance in high pressure arcs. The radiation transport model of [2] for nitrogen nozzle arc is adopted. In the high temperature core the boundary of which is defined as 83% of the axis temperature net radiation loss per unit volume and time is equal to the net emission coefficient of [6] as a function of pressure, arc radius and temperature for nitrogen. There are considerable differences between the computed net emission coefficients for air [7]. Net emission coefficient for nitrogen is slightly smaller than that of air. However, when a comparison is made between the net emission coefficients for nitrogen [6] and those for air [7] the values given in [6] are more than twice larger than those of [7]. Since the radiation data of [6] are consistent with experiments on wall stabilised arcs and give satisfactory agreement with temperature measurements of a nitrogen nozzle arc [2], the radiation data of [6] are used. 60% of the radiation flux at the core boundary is assumed to escape from the arc. This gives approximately 40% to 50% of total electrical power input of the arc to be taken out by radiation. This is consistent with the radiation loss measurements of [8] for a copper electrode. Experimental results of [3] indicate that upstream electrode vapour entrains into the arc, thus greatly increasing arc radiation. To account for this a factor of 2 is multiplied to the radiation data of [6].

The experimental systems at entry Mach number (M) of 0.2 and 0.8 respectively [3] are approximated by those shown in Fig. 1. The mass flow rate at the inlet of M=0.2 is iteratively computed with the specified upstream stagnation pressure and temperature (Fig. 1(a)) while for M=0.8 system the mass flow rate is fixed at 400 $kg/(s \cdot m^2)$ at a temperature of 300 K while the inlet pressure is iteratively calculated. At the inlet, turbulent kinetic energy is set at 5% of the kinetic energy of the entry flow and the dissipation rate at entrance follows that given in [9]. The pressure at the outlets is set at 1atm and the normal derivatives of enthalpy, velocity components and electrical potential are set to zero. Uniform current distribution at the upstream elkonite electrode is assumed. The arc length is 10 cm and other dimensions are shown in Fig. 1. Version 3.6.1 of PHOENICS [9] has been used to obtain results.



(a) Mach number = 0.2

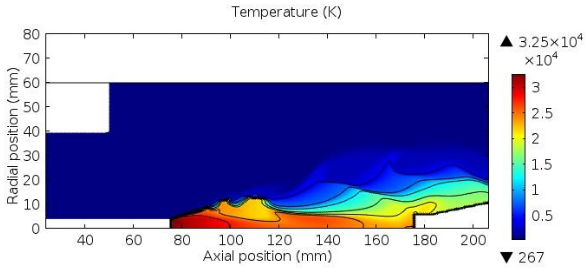


(b) Mach number = 0.8

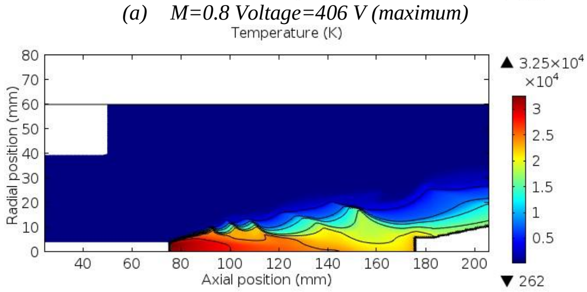
Fig.1 System geometry and dimensions in mm

3. RESULTS AND DISCUSSION

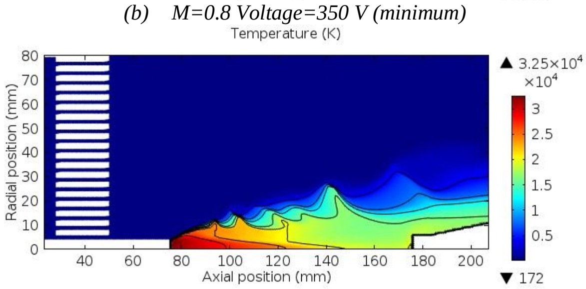
Four cases have been computed for currents at 5 kA and 10 kA with entry Mach number at 0.2 and 0.8 (Table 1). The striking feature of the results is the wavy shape of the arc column (Fig. 2). Other features are similar to those of a free burning arc. Radial component of the Lorentz force creates a radial pressure gradient the axis pressure of which depends on the radius of electrically conducting core (hereafter referred to as arc radius). Since the arc radius is smallest at the upstream electrode, pressure within the arc conducting core drops rapidly in the axial direction due to arc expansion downstream. This results in rapid acceleration of the arc plasma (Fig. 3). Plasma acceleration by magnetic pinch effect is commonly known as magnetic pumping. The highest axis velocity attains 8,000 m/s for 10 kA arc at M=0.8. To maintain mass balance within the arc, cold flow needs to enter the hot region. The boundary of arc thermal influence (thus arc size) is determined by the mass balance between the mass transported by the accelerating flow in the arc core and the flow entrainment. For an arc at 10 kA in a jet with M=0.2, pressure gradient on axis is very similar to that of 10 kA at M=0.8. Thus, axis velocity is almost same for the two arcs (Fig. 3). Because the flow in the surrounding jet for M=0.2 is nearly 4 times smaller than that of M=0.8 the arc size for M=0.2 is bigger in order to maintain mass balance, thus reducing the arc voltage (Table 1).



(a) M=0.8 Voltage=406 V (maximum)



(b) M=0.8 Voltage=350 V (minimum)



(c) M=0.2 Voltage=261 V

Fig. 2 Temperature distributions together with isotherms at 10 kA. The isotherms from the arc core to the arc boundary indicate respectively the temperature values of 28000 K, 24000 K, 20000 K, 16000 K, 12000 K, 8000 K and 4000 K.

Table 1 Measured and computed arc voltage

Arc Voltage (V)	Experiment		Simulation (mean)	
Current	Mach Number		Mach Number	
	0.2	0.8	0.2	0.8
5 kA	280	330	210	328
10 kA	310	380	261	378

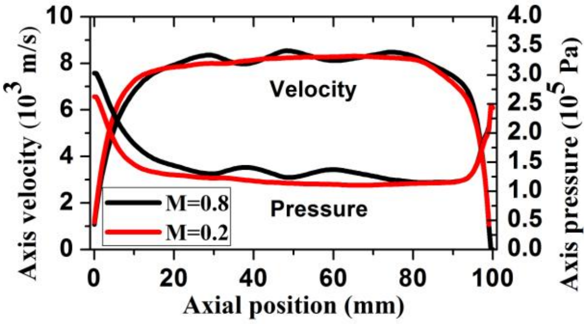


Fig. 3 Axis velocity and pressure distribution: 10 kA, M= 0.8 and 0.2. Zero position indicates upstream electrode tip.

When current is reduced to 5 kA, the qualitative features of the arc remain the same as those of 10 kA case. However, due to the over pressure in an arc cross section caused by magnetic pinching is proportional to the square of current, magnetic pumping effects are much weaker than the 10 kA case. The axis velocity of the 5 kA arc is greatly reduced. Arc voltage is lower than that of the 10 kA arc at the same Mach number because radiation loss and enthalpy transport for 5 kA arc are both reduced due to reduced pressure and velocity within the arc.

Arc voltage oscillation is most pronounced for 10 kA arc with M=0.8. Such voltage oscillation is associated with the continuous change of arc shape with a period of approximately 0.5 ms. The average voltage is 378 V with oscillating amplitude of ±28 V (±7% around the mean). The arc shape of Fig. 2(a) corresponds to the maximum arc voltage and Fig. 2(b) the minimum. When an arc is drawn between two electrodes located inside a round jet pressure waves are created which propagate through the jet and are reflected at the outlet (Fig. 1) where the pressure is fixed at 1 atm. Disturbance to the jet caused by the arc depends on the arc current for a given jet Mach number as the current determines the volume of arc's thermal influence region. When this volume is an appreciable fraction of the jet volume, the pressure within the jet will be substantially changed, which in turn affects the pressure seen by the thermal region (where temperature is below 4,000 K at which electrical conductivity is taken as zero). The closed coupling between the arc and its surrounding jet and the pressure waves reflected from the fixed pressure outlets result in periodic pressure waves established within the system. Pressure distribution within the system corresponding to an arc voltage of 378 V is given in Fig. 4. Axial pressure distribution along a fixed radius (e.g. 1.5 cm) is no longer monotonic. In the region where pressure reduces, the gas is accelerated. The arc therefore contracts. The arc expands in the region where pressure increases. Arc contraction and expansion result in the wavy shape of the arc. The period of voltage oscillation, approximately 0.5 ms, is close to the time required for a sound wave at 340 m/s to make a round trip of a 10 cm long arc.

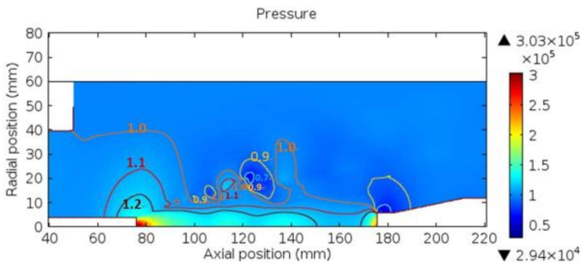


Fig. 4 Pressure distribution for 10kA, arc voltage= 378 V and M=0.8

When current is reduced to 5 kA with M=0.8 the disturbance to pressure within the jet is much smaller than the 10 kA case. The strength of reflected waves is also much reduced, thus the arc shape varies very little during a period of oscillation. The amplitude of voltage oscillation around the mean value is less than ±1.5%. The diameter of the jet with M= 0.2 is twice that of M=0.8 jet. Thus its volume is 4 times larger than the jet with M=0.8. The disturbance caused by the arc in a jet with M=0.2 at 10 kA or 2 kA is expected to be much small than its counterpart in M=0.8 case. Voltage oscillation for M=0.2 is reduced to ±1.5% around the mean. Due to the scatter of measured arc voltage of around 10% the predicted voltage oscillation below experimental scatter will not be observed experimentally. Periodical voltage oscillation with similar period has been observed experimentally [3] although at a higher current than 10 kA.

It is important to assess the dominant energy transport process which determines the characteristics of the arc. Since the arc is burning in a turbulent jet, it is of interest to see whether turbulence is able to penetrate into the high temperature core. Energy balance calculation to the boundary of the high temperature core shows that radiation almost balances Ohmic input and turbulent radial thermal conduction is negligible. The high temperature core carries on average of 65% of the total current for the 4 cases computed. Energy balance calculation to the boundary of electrically conducting core reveals that radial turbulent thermal conduction accounts for less than 10% of the electrical power input for the three cases investigated (Table 2). Energy transport by radiation, axial and radial enthalpy transport are all important.

Table 2 Percentage of electrical power input taken out by various energy transport processes at the boundary of high temperature core and at the boundary of electrically conducting core. Negative sign means power loss and positive power input. Energy transport due to pressure work and the contribution to energy balance due to rate of change of energy storage are not shown.

	Mach	Current (kA)	Power input (MW)	Radiation loss (%)	Radial thermal turbulent conduction (%)	Axial enthalpy convection (%)	Radial enthalpy convection (%)
0.83 by high temperature core	0.8	10	2.49	-98.4	-1.3	12.1	7.5
		5	0.96	-107.8	-2.1	15.2	0.4
	0.2	10	1.70	-111.7	-1.7	21.9	8.4
		5	0.64	-117.2	-3.4	28.5	6.0
4000 K by electrically conducting core	0.8	10	3.62	-40.9	-13.0	-87.0	53.3
		5	1.58	-39.9	-8.5	-99.2	65.5
	0.2	10	2.48	-47.9	-5.9	-23.3	-10.9
		5	1.00	-47.2	-8.8	-22.1	-11.3

In comparison with experimentally measured arc voltage (Table 1) the computed mean voltage for M=0.8 jet agrees well with that measured. However, for M=0.2, the difference between the computed mean arc voltage and that measured is larger than the experimental scatter [3]. Such discrepancy is probably caused by the over prediction of arc radius. In practice [3] electrode vapour due to the melting of upstream electrode entrains into the arc, which modifies radiation and increases electrical conductivity. The latter may result in a smaller electrically conducting core due to increased electrical conductivity, thus increasing magnetic pumping.

4. CONCLUSIONS

DC arcs at 10 kA and 5 kA burning in a turbulent round jet with an entry Mach number of 0.8 and 0.2 have been computationally investigated. It has been found that pressure waves within the system are responsible for the wavy shape of the arc and for the voltage oscillation with a period of approximately 0.5 ms. Turbulent transport of energy accounts for less than 10% of electrical input. For the high temperature arc core, turbulence transport can be neglected as it cannot penetrate the high temperature region.

There is a large discrepancy between the predicted arc voltage and that measured for M=0.2 case. Possible causes for such a discrepancy have been suggested. Further work needs to be done to account for the effects of electrode vapour on radiation and transport properties.

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