Influence of metal vapour on arc temperatures in gas–metal arc welding: convection versus radiation

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Abstract

The presence of metal vapour in gas–metal arc welding has been shown to have two strong effects on the arc plasma: a decrease in temperature throughout the arc, and the formation of a local temperature minimum near the arc axis. These effects have been attributed, on the basis of different computational models, to either the increased radiative emission associated with the presence of metal vapour in the arc plasma, or the influence of the metal vapour influx on convective flow in the arc. This question is investigated using a three-dimensional computational model in which the production and the transport of metal vapour are taken into account self-consistently. Parameters relevant to welding of thin sheets of aluminium are examined. For these conditions, it is found that the first effect (the decrease in temperature throughout the arc) is due to both the increased radiative emission and the influence of the metal vapour influx on flow. The second effect (the local temperature minimum, which in this case occurs just below the wire electrode) is a consequence of the influence of aluminium vapour produced from the wire electrode on flow in the arc. By examining published results and the energy balance in the plasma, it is shown that for welding of steel with higher arc currents, the increased radiative emission can lead to a local temperature minimum at a greater distance from the wire electrode.
1 Introduction

The large thermal fluxes associated with thermal arc plasmas typically leads to significant evaporation of the electrodes, particularly when they are made of non-refractory metals. The metal vapour that is produced can strongly influence the properties of the arc plasma, and the interaction of the plasma with the electrode. An example is gas–metal arc welding (GMAW; also known as metal–inert-gas or metal–active-gas welding), which is a very widely-used method to join metals [1].

In GMAW, an electric arc is struck between two electrodes, a metal wire and the workpiece (i.e. the pieces of metal being joined). The tip of the wire electrode, which is usually the anode, melts, and droplets of molten metal detach and pass through the arc into the weld pool (the molten region of the workpiece). The shielding gas in GMAW is usually argon, a mixture of argon and oxygen, a mixture of argon and carbon dioxide, or carbon dioxide [2]. Because of vaporization of the molten regions of the electrodes and the droplets, the concentration of metal vapour in the arc can become very high, reaching at least 50% [1, 3, 4].

The presence of metal vapour is found to have two major effects on the temperature distribution in the arc. First, the temperature is strongly decreased. Second, a local minimum in the dependence of temperature on arc radius is formed on the arc axis. Both these effects have been demonstrated experimentally. For example, the maximum temperature in a gas–tungsten arc welding (GTAW) arc with a water-cooled workpiece, in which essentially no metal vapour is produced, has been measured to be about 20 000 K or more, for argon shielding gas and an arc current of 100 A or more [5, 6] . The maximum temperature of a GMAW arc with steel electrodes and argon shielding gas is much lower; for example Valensi et al. [7] and Zielinska et al. [8] both measured a maximum temperature of around 12 000 K for argon shielding gas and arc current of 330 A, and Rouffet et al. [4] obtained around 13 000 K for an arc current of 420 A. The local temperature minimum has been reported by all these authors. The results of Zielinska et al. [8] are shown in Figure 1; it can be seen that the minimum occurs for a range of axial distances from the wire electrode, with the temperature falling to about 8000 K or less on axis.
Figure 1. Radial dependence of electron temperature for 326 A arc in argon. Axial positions are ▲ 3 mm, ■ 4.5 mm and ● 6.0 mm above the workpiece. From Zielinska et al. [8].

While the two effects have been demonstrated experimentally, their physical cause is a subject of some controversy. Schnick et al. [9, 10] attributed both effects to the strong increase in radiative emission that occurs when metal vapour is added to argon or the other shielding gases. Haidar [11] argued that the influence of the production of metal vapour from the wire on the flow in the arc was sufficient to explain both effects. Both Schnick et al. and Haidar based their results on numerical models with some shortcomings, so it is not possible to determine a definitive answer from their results. Schnick et al. used a estimates of the vaporization rate of the wire and the distribution of the vapour as it enters the arc. Haidar did calculate the vaporization rate and distribution, but did not take into account the cooling of the wire due to the latent heat of vaporization, and so overestimated the rate. Haidar also did not include the influence of the increased radiative emission from the metal vapour, nor the diffusive mixing of the metal vapour with the shielding gas.

In this paper, I present results obtained using a three-dimensional computational model of GMAW that includes the electrodes in the computational domain, and treats formation of metal vapour self consistently. This allows the production rate and the distribution of the metal vapour near the wire to be calculated, rather than estimated. Further, the influence of the metal vapour on radiative emission, and the diffusive mixing of the metal vapour, are both taken into account.

The model is applied to the welding of thin aluminium sheets, for which the arc current is relatively low. By considering the results obtained, comparing them to the results of Schnick et al. [9, 10] and Haidar [11], and examining the underlying physics, an understanding is
developed of the reasons for the relatively-low temperature, and the local temperature minimum, that have been observed in GMAW arcs. Through this understanding, the differences between the results of Schnick et al. and Haidar can be at least partially resolved.

2 Computational model

The computational model solves the equations of mass continuity, momentum conservation, energy conservation, metal vapour mass conservation and current continuity in three dimensions. The equations are solved simultaneously in the electrodes and plasma, with appropriate interface and boundary conditions between the different phases. Only steady-state welding conditions are considered here, so time-dependent terms are omitted.

Details of the model without the influence of metal vapour have been given previously [12]. Here the model is outlined briefly, emphasising the changes required when metal vapour is considered.

The momentum conservation equation is

\[
\nabla \cdot \left[ \rho (\mathbf{v} - \mathbf{V})(\mathbf{v} - \mathbf{V}) \right] = -\nabla P + \nabla \cdot \mathbf{\tau} + j \times \mathbf{B} + \rho \mathbf{g}, 
\]

where \( \rho \) is the mass density, \( \mathbf{v} \) is the flow velocity of the plasma or liquid metal, \( \mathbf{V} \) is the velocity with which the wire electrode moves with respect to the workpiece (the welding velocity), \( P \) is the pressure, \( \mathbf{\tau} \) is the viscous stress tensor, \( j \) is the current density, \( \mathbf{B} \) is the magnetic field strength induced by the current, and \( \mathbf{g} \) is the acceleration due to gravity. The viscous stress tensor \( \mathbf{\tau} \) is given by

\[
\tau_{ii} = \eta \left( \frac{2}{3} \frac{\partial \mathbf{v}_i}{\partial x_i} \right), \quad \tau_{ij} = \eta \left( \frac{\partial \mathbf{v}_i}{\partial x_j} + \frac{\partial \mathbf{v}_j}{\partial x_i} \right), \quad i \neq j, 
\]

where \( \mathbf{v}_i \) and \( x_i \) are respectively the components of the velocity and position in the \( i = x, y \) or \( z \) direction, and \( \eta \) is the viscosity.

The energy conservation equation is
\begin{equation}
\n\nabla \left[ \rho (v - V) \right] = \frac{J^2}{\sigma} - \nabla \left( \frac{k}{c_p} \nabla h \right) - \nabla \left[ \frac{h_M - h_S}{c_p} \nabla Y^M \right] - \frac{5k_B}{2e c_p} j \cdot \nabla h - U - S_{vap}, \quad (3)
\end{equation}

where \( h \) is the enthalpy, \( \sigma \) is the electrical conductivity, \( k \) is the thermal conductivity, \( c_p \) is the specific heat at constant pressure, \( h_M \) and \( h_S \) are respectively the enthalpies of the metal vapour and shielding gas, \( Y^M \) is the sum of the mass fractions of the metal vapour species (atoms, ions etc), \( k_B \) is Boltzmann’s constant, \( e \) is the electronic charge, \( U \) is the net radiative emission coefficient, and \( S_{vap} \) is the latent heat of vaporization, which is non-zero only in control volumes at the edge of the wire electrode and workpiece. The term in \( \nabla Y^M \) is added to account for the change in enthalpy resulting from mixing of the metal vapour and the shielding gas; it is required since the thermal conduction term is written in terms of the enthalpy rather than the temperature, and since \( \nabla h = C_p \nabla T + \sum_i h_i \nabla Y_i \), where \( h_i \) and \( Y_i \) are respectively the enthalpy and mass fraction of species \( i \).

As well as cooling the wire electrode and workpiece by latent heat of vaporization, the production of metal vapour transfers energy to the plasma. Following Haidar [11], the convection term in the energy conservation equation \( \nabla \cdot (\rho v h) = h \nabla \cdot (\rho v) + \rho v \cdot \nabla h \) is replaced by \( S_{hv} + \rho v \cdot \nabla h \), where

\begin{equation}
S_{hv} = J_{vap} h(T_{el}) A/\Delta V, \quad (4)
\end{equation}

\( J_{vap} \) is the metal vapour mass flux, given in (7) below, and \( h(T_{el}) \) is the enthalpy of the vapour at the temperature \( T_{el} \) of the metal control volume immediately adjacent to the plasma [17]. Since the source term is added to the plasma control volume adjacent to the metal, \( \Delta V \) is the volume of the plasma control volume adjacent to the surface and \( A \) is the area of the control volume face at the metal surface.

An additional equation is required to describe the conservation of the metal vapour mass

\begin{equation}
\nabla \cdot (\rho v Y^M) = -\nabla \cdot \mathbf{J}_M + S_M, \quad (5)
\end{equation}

where \( \mathbf{J}_M \) is the average mass flux, relative to the mass-average velocity, of the metal vapour species, and \( S_M \) is the metal vapour source term associated with the production of
metal vapour due to evaporation of the electrodes and droplets (the net production of mass per unit volume and time) [1].

The mass flux $\overrightarrow{J_M}$ is calculated using the combined diffusion coefficient method [13, 14], and is given by

$$\overrightarrow{J_M} = \frac{n^2}{\rho} \overline{m_M m_G} \left( \overline{D_{MG} \nabla x_G} + \overline{D^E_{MG} E} \right) - \overline{D^T_{MG}} \nabla \ln T,$$

(6)

where $\overline{m_M}$ and $\overline{m_G}$ are respectively the average masses of the heavy species of the metal vapour and the shielding gas and $\overline{x_G}$ is the sum of the mole fractions of the species of the shielding gas; $\nabla x_G = -\nabla x_M$. The combined ordinary diffusion coefficient $\overline{D^1_{MG}}$, combined electric field diffusion coefficient $\overline{D^E_{MG}}$ and combined temperature diffusion coefficient $\overline{D^T_{MG}}$ describe, respectively, diffusion due to mole fraction gradients, externally-applied electric fields and temperature gradients. They are linear combinations of the multicomponent diffusion coefficients; expressions are given in [13, 14].

The metal vapour source term $S_M = J_{vap} A/\Delta V$ is calculated from the expression for the net vaporization mass flux $J_{vap}$ given by Barrett and Clement [15], which gives close agreement with more complex expressions obtained by solution of the Boltzmann transport equation:

$$J_{vap} = \frac{16}{9} \left( \frac{m_M}{2 \pi k_B} \right)^{1/2} \frac{P_{vap}}{T_i^2} \left( \frac{P_{vap} - P_\infty}{P_{vap}} \right).$$

(7)

Here $m_M$ is the mass of a metal atom, $P_\infty$ is the metal vapour partial pressure at a position distant from the metal surface, and $P_{vap}$ is the vapour pressure at the temperature $T_i$ of the metal surface, given by the Clausius–Clapeyron equation:

$$P_{vap} = P_{atm} \exp \left[ \frac{-H_{vap}}{R} \left( \frac{1}{T_i} - \frac{1}{T_b} \right) \right]$$

(1.8)

where $P_{atm}$ is atmospheric pressure, $H_{vap}$ is the molar heat of evaporation, $T_b$ is the boiling temperature of the metal at atmospheric pressure, and $R$ is the ideal gas constant.

The mass continuity equation also includes the metal vapour source term:
\[ \nabla \cdot (\rho \mathbf{v}) = S_M. \]  

The current continuity equation is

\[ \nabla \cdot (\sigma \nabla \phi) = 0. \]  

The current density is related to the electric potential \( \phi \) by

\[ j = -\sigma \nabla \phi. \]  

The magnetic field strength \( \mathbf{B} \) is calculated using \( \mathbf{B} = \nabla \times \mathbf{A} \), with the magnetic potential \( \mathbf{A} \) determined by solving

\[ \nabla^2 \mathbf{A} = -\mu_0 j. \]  

where \( \mu_0 \) is the permeability of free space.

The different phases are differentiated by their different thermophysical properties. In the solid regions, the mass continuity and momentum conservation equations are not required since there is no flow.

Boundary conditions, and the treatment of the interfaces between the arc plasma and the wire electrode, the arc plasma and the workpiece, and the solid and liquid regions of the workpiece, were presented previously [12].

The surface profile of the weld pool is calculated as described previously [12], using an equilibrium surface method [16, 17]. This requires minimizing the total surface energy, taking into account the surface tension energy, the gravitational potential energy, and the work performed on the surface by the arc pressure and droplet pressure. The overall height increase, relative to the initial workpiece surface, is restricted to be consistent with the mass added through droplet transfer.

The methods used to calculated the momentum and energy transferred to and from the droplets as they pass through the arc and into the weld pool, and the evaporation of metal vapour from the droplets in the arc, have been described in detail elsewhere [18]. The momentum, energy and mass transfer are averaged over time and the spatial extent of the
droplets. It should be noted that the treatment of droplets as they enter the weld pool has been modified \[18\] with respect to that given in Ref. \[12\].

3 Results and discussion

3.1 Parameters

Calculations were performed with an initially flat workpiece (i.e., bead-on-plate welding), and for constant welding speed and arc current. The welding parameters considered are typical of one-drop-per-pulse welding of thin sheets of aluminium, as is commonly performed in the automotive industry. The parameters are listed in Table 1. Consistent with the time-averaging of the influence of the droplets on the arc and weld pool, a constant arc current (equal to the time-average of the step waveform) is used in the model. A flat electrode tip is used. The same conditions were used in \[12\], except that the workpiece is thinner in the current paper.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc current</td>
<td>95 A</td>
</tr>
<tr>
<td>Wire electrode radius</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Welding velocity</td>
<td>15 mm s(^{-1}) in negative y direction</td>
</tr>
<tr>
<td>Wire electrode feed rate (v_e)</td>
<td>72 mm s(^{-1})</td>
</tr>
<tr>
<td>Droplet frequency</td>
<td>93 Hz</td>
</tr>
<tr>
<td>Workpiece thickness</td>
<td>3 mm</td>
</tr>
<tr>
<td>Electrode–workpiece distance</td>
<td>5 mm (before arc initiation)</td>
</tr>
</tbody>
</table>

The conservation equations were solved using the finite-volume method described by Patankar \[19\]. Details of the mesh and computational methods have been given previously \[12\].

The thermophysical properties of argon–aluminium vapour mixtures were calculated as described by Murphy \[1\]. Note that the values of \(D_{MG}^T\) given in Ref. \[1\] were in fact those of \(-D_{MG}^T = D_{GM}^T\) .

The net radiative emission coefficients, for a 1 mm absorption length, were taken from Cram \[20\] for argon, Essoltani et al. \[21\] for aluminium vapour, and Menart and Malik \[22\] for iron vapour. These data are shown in Figure 2. The net emission coefficients for mixtures of argon and metal vapour were determined by a linear interpolation of those of the pure gases based on the mole fraction, as recommended by Gleizes et al. \[23\].
3.2 Influence of metal vapour on the arc

The influence of metal vapour in the arc properties can be determined by comparing results obtained using the computational model presented in section 2, and those neglecting the influence of metal vapour, i.e. from a modified model in which equation (5), and the metal vapour terms in (3) and (9), are omitted. Figure 3 shows the temperature distribution obtained considering and neglecting the formation of metal vapour. It is clear that the presence of metal vapour strongly decreases the arc temperature. The maximum temperature in the presence of metal vapour is 9800 K, and without metal vapour 14 000 K. In addition to the much lower temperature, a local temperature minimum is apparent in the metal vapour case, extending on axis for about 1 mm below the wire tip.
Figure 3. Distribution of temperature in the $x = 0$ plane including (left) and neglecting (right) the influence of metal vapour.

Figure 4 shows the metal vapour mass fraction distribution in the arc. Most of the aluminium vapour is produced at the wire electrode. The vaporization rate is $1.7 \times 10^{-2}$ g s$^{-1}$, or 7.9% of the wire mass feed rate (the remainder of the wire is converted into droplets). The vaporization rate of the weld pool is $1.0 \times 10^{-3}$ g s$^{-1}$, and that of the droplets is lower again.

The metal vapour remains concentrated near the arc axis, with its mass fraction remaining above 0.5 at all vertical positions. This is due to the strong downwards convective flow. The flow speed has a maximum value of 80 m s$^{-1}$, and is driven mainly by the magnetic pinch force and the evaporation of vapour from the wire tip.
An interesting effect is visible in the distribution of metal vapour shown in Figure 4. Local minima in the aluminium mass fraction occur near the workpiece at \( y \approx \pm1.5 \) mm. The corresponding temperature is around 7000 K, which is the temperature at which aluminium ionizes. This is a consequence of demixing due to mole fraction gradients, which leads to a local minimum in the mass fraction of a gas at its ionization temperature. This phenomenon has been demonstrated previously for welding gas mixtures such as argon and helium [24].

It was noted above that a local minimum in temperature near the arc axis occurs for axial positions within about 1 mm of the wire tip when metal vapour is considered. To investigate this effect, as well as the reasons for the overall decrease in arc temperature, three additional calculations were performed. The results are shown in Figure 5, which gives the temperature along a horizontal line through the arc axis, at an axial position 0.7 mm below the wire tip. The ‘Al NEC’ curve is the standard case, for which \( U = x_{Al}U_{Al} + x_{Ar}U_{Ar} \), where \( x_I \) is the mole fraction and \( U_I \) is the net emission coefficient of gas \( I \). For the ‘Fe NEC’ curve, the net
emission coefficients for aluminium were replaced by those for iron, so \( U = x_{\text{Al}} U_{\text{Fe}} + x_{\text{Ar}} U_{\text{Ar}} \).

The net emission coefficients for argon were used for the whole plasma, irrespective of its composition (i.e. \( U = U_{\text{Ar}} \) everywhere), for the ‘Ar NEC’ curve. Finally, for the ‘Al NEC; mass source neglected’ curve, the metal vapour source term in the mass conservation equation (9) was neglected, and \( U = x_{\text{Al}} U_{\text{Al}} + x_{\text{Ar}} U_{\text{Ar}} \).

It is clear from the figure that radiative emission has a significant influence on the arc temperature. As shown in Figure 2, the net emission coefficients for argon are much lower than those for aluminium, which are in turn much lower than those for iron. The calculated radiative loss for the whole arc is 20, 600 and 1280 W for the respective cases of argon, aluminium and iron net emission coefficients. As shown in Figure 5, the temperature is reduced at all points in the arc when the radiative emission coefficient increases.

However, the inclusion of the metal vapour source term also has an influence on the arc temperature. This is apparent through comparison of the left-hand side of Figure 3, in which all influences of metal vapour are neglected, and the ‘Ar NEC’ curve in Figure 5, for which the metal vapour source term is included, but the effect of metal vapour on the net emission coefficient is neglected. The temperature is much lower in the latter case.

It can therefore be concluded that both increased radiative emission, and the influx of relatively-cold metal vapour from the wire electrode, contribute strongly to the decrease in arc temperature that occurs when metal vapour is present.

It is also clear from Figure 5 that the local minimum in temperature occurs on axis irrespective of the strength of radiative emission. Only when the metal vapour source term in the mass conservation equation is neglected does the local temperature minimum disappear.
Figure 5. Dependence of temperature on horizontal position at an axial position 0.7 mm below the wire tip and at \( x = 0 \), for four different cases, defined in the text.

To allow this effect to be investigated further, the vertical speed of the plasma flow is shown in Figure 6, for the same parameters used in Figure 5. When the metal vapour mass source is neglected, there is a strong local minimum in flow speed on the axis. The flow speed off-axis is higher. This is because the flow is driven almost exclusively by the magnetic pinch force, which is largest near the edges of the wire electrode tip, since the current density is highest at the edges. When the influence of metal vapour is included, the flow velocity has a much weaker dependence on horizontal position. For the cases in which argon or aluminium net emission coefficients are used, there are three peaks. The two outside peaks are due to the magnetic pinch force. The central peak is due to the production of metal vapour, which increases the local pressure and drives flow downwards away from the wire electrode tip [11]. The central peak is not present for the case in which iron net emission coefficients are used, possibly due to the increased viscosity; the maximum viscosity in a plasma dominated by metal vapour occurs at about 7000 K [1], which is the temperature calculated near the arc axis in this case (see Figure 5).
3.3 Influence of metal vapour on the weld pool

Since the computational model includes the workpiece self-consistently, and determines the shape of the weld pool surface and flow in the weld pool, it is possible to predict the weld pool depth and shape. Figure 7 shows the predicted weld cross-sections calculated including and neglecting the influence of metal vapour, and a measured weld cross-section. It is clear that the weld pool is shallower when metal vapour is considered, and that this brings the predicted weld cross-section into good agreement with the measured cross-section.
Figure 7. Comparison of measured weld cross-section with those calculated including and neglecting the influence of metal vapour.

The net energy transfer from the arc to the workpiece is calculated as the sum of five terms: thermal conduction, the energy transferred by electric current (which is given by $j(V_c - \phi_w)$, where $V_c$ is the cathode voltage drop, set to 12 V, and $\phi_w$ is the work function of the workpiece material, set to 3 V [12]), the energy transferred by droplets, blackbody radiation from the workpiece surface, and latent heat of vaporization of the metal vapour. The first three are heating terms, and the latter two are cooling terms.

The thermal conduction to the workpiece is reduced by the presence of metal vapour, from 610 to 470 W for the parameters investigated here, since the plasma temperature is decreased. While the total heat transferred by electric current, 855 W, is not influenced by the presence of metal vapour (since the total current remains the same), its distribution is affected. Metal vapour increases the electrical conductivity of the plasma at low temperatures, which means that current can be conducted through a larger horizontal cross-section of the plasma, thus decreasing the current density, and leading to a lower heat flux density. The heat transferred by droplets is similar in both cases, and blackbody radiation is negligible in both cases. The latent heat of vaporization is of course only present when metal vapour is considered, and for the parameters considered was only 16 W. The two dominant effects of metal vapour on heat
transfer to the workpiece are therefore the reduced thermal conduction, and the decreased current density.

3.4 Comparison with other results

The results presented here indicate that for a relatively low current (95 A) arc with aluminium electrodes, the production of metal vapour leads to a significant decrease in temperature throughout the arc plasma, and a local temperature minimum on the arc axis close to tip of the wire electrode. Further, it has been shown that both the increased radiative emission associated with the presence of metal vapour, and the influx of relatively cool vapour from the wire electrode, contribute significantly to the cooling of the arc. Finally, the local temperature minimum below the wire electrode has been attributed to the influx of metal vapour rather than increased radiative emission.

It is important to compare these results with those of other workers to obtain a more comprehensive picture of the influence of metal vapour on the temperature of the arc plasma. In doing this, three parameters are considered: the arc current and the electrode composition in section 3.4.1, and the distribution of the metal vapour flux emanating from the wire electrode in section 3.4.2.

3.4.1 Arc current and electrode composition

Schnick et al. [9, 10] presented results for iron electrodes for three different arc currents: 100 A, 250 A and 400 A. The input flux of metal vapour used was 0.015 g s\(^{-1}\), which is very similar to that calculated here (0.017 g s\(^{-1}\)). Results for 100 A and 250A are given in Figure 8.

Schnick et al. found that a local temperature minimum occurred on axis, beginning about 2 mm below the wire tip and extending to the workpiece, for the higher two currents. For the 100 A arc, the radial temperature profile was approximately flat near the arc axis, with a very shallow temperature minimum.
Schnick et al. showed that the main physical factor responsible for the local temperature minimum was the increased radiative emission due to the presence of iron vapour. This was done by performing a calculation taking into account the presence of iron vapour, but using argon net emission coefficients (as was done for the ‘Ar NEC’ curve in Figure 5). They found that, although the temperature was about 1000 K lower than predicted in the absence of the iron vapour, the local temperature minimum disappeared.

A simple energy balance, taking into account ohmic heating and radiative cooling, can be used to investigate the influence of radiative emission in producing a local temperature minimum [25]. In this approximation, a temperature minimum at a given position requires...
radiative cooling $U$ to be larger than ohmic heating $j^2/\sigma$ at that position; i.e.,
\[ B = j^2/\sigma - U < 0. \]
Since $\sigma$ and $U$ are strongly dependent on temperature, $B$ is also a strong function of temperature.

The approximation neglects the influence of convection and thermal conduction. Conduction opposes the formation of a temperature minimum, since it will act to heat a region with temperature below that of neighbouring regions. While it has been shown above that the strong convective flow from the wire electrode can cool the plasma, convection from a hotter upstream region will heat the downstream plasma. Thus, in cases such as that shown in Figure 8(a), in which the temperature minimum is formed well below the wire electrode, both convection and conduction will oppose the formation of a temperature minimum. $B(T) < 0$ is therefore a necessary, but not sufficient, requirement for the formation of the local temperature minimum in regions well below the wire electrode.

Figure 9(a) shows $j^2/\sigma(T)$ and $U(T)$ for mixtures of 50% argon and 50% iron vapour, and 50% argon and 50% aluminium vapour, for current densities of 7, 10 and 15 A mm$^{-2}$. The current density on axis for a 95 A GMAW arc is around 8 A mm$^{-2}$; this increases with arc current, but the dependence is weaker than linear, since the as current increases, it tends to flow over a wider cross-sectional area. The ohmic heating is almost independent of the type of metal vapour, except at temperatures below about 8000 K, for which the electrical conductivity of aluminium is higher. The radiative loss is much greater for iron than aluminium, as expected from Figure 2.
Figure 9. Power balance in argon arcs with aluminium or iron vapour as a function of temperature, for different current densities. Results are given for a mixture of 50 mol% Ar with 50 mol% Al or Fe. (a) Ohmic heating and radiative loss; (b) Difference between ohmic heating and radiative loss, $B$.

Figure 9(b) shows the factor $B(T)$ for the same parameters used in Figure 9(a). In the case of iron vapour, $B(T) < 0$ above a relatively low threshold temperature, between 7000 K and 8600 K for the current density range considered. For aluminium vapour, the corresponding
temperatures are 10 000 K and 14 900 K. This clearly indicates that the low radiative emission from aluminium makes the formation of a temperature minimum much less likely. For the 95 A arc current considered here, the temperature only reaches about 10 000 K, so the formation of a local temperature minimum due to radiative emission is not expected.

The arc temperature becomes higher when the arc current is increased because of the stronger ohmic heating, so the formation of a local temperature minimum caused by radiative emission becomes more likely. This is evident in the results of Schnick et al. discussed above, for which the minimum is weak or non-existent for 100 A, in which the maximum temperature is about 9000 K, and strong for 250 A, for which the maximum temperature is 15 000 K. Further, Boselli et al. [26] recently presented modelling results for different currents in a typical droplet formation and detachment cycle for iron electrodes, finding that a temperature minimum occurred for currents above 150 A, but not for lower currents. While the results were somewhat complicated by the presence of droplets in their model for some of the currents, they are nonetheless consistent with those of Schnick et al.

It is worth noting that the current density is higher near the wire electrode tip, so a local temperature minimum is less likely in this region because of the increased ohmic heating.

3.4.2 Metal vapour flux distribution
Haidar [11] presented results for a range of different wire electrode shapes, and iron vapour fluxes. The arc current was 150 A in all cases. Here I consider his results for a flux of 0.0175 g s⁻¹ and wire diameter of 1 mm, shown in Figure 10(a), since this is very close to the flux calculated here (0.017 g s⁻¹) and the wire tip diameter used here (1.2 mm). Haidar found a local temperature minimum on axis, extending downwards from the wire tip for about 3 mm. This is about 2 mm further than that obtained here. As noted previously, Haidar neglected the influence of metal vapour on the net radiative emission coefficient, and also the diffusive mixing of the metal vapour in the arc. The latter approximation meant that the metal vapour distribution was more strongly confined near the arc axis, which exaggerated the cooling effect of the metal vapour flux.

Haidar also presented results for different wire electrode tip shapes. He found that no local temperature minimum occurred for a tip in the form of a rounded droplet just prior to detachment, as shown in Figure 10(b), despite the mass flux of evaporating vapour being much higher (0.099 g s⁻¹) than that for Figure 10(a). The absence of a local temperature minimum was because the droplet metal was at an approximately uniform temperature, which
meant the metal vapour evaporated from the top and sides as well as the bottom of the rounded tip, and hence was not concentrated in the region below the wire electrode tip.

Figure 10. Temperature in the arc and electrodes for two different wire shapes, (a) with diameter 1 mm and rounded end; flux of iron vapour from the wire is 0.0175 g s$^{-1}$, and (b) with large droplet just before detachment; flux of iron vapour from the wire is 0.099 g s$^{-1}$. The arc current is 150 A, and the influence of iron on the radiative emission coefficient, and the diffusion of iron in the arc plasma, are neglected. From Haidar [11].
Schnick et al. [9] used an assumed metal vapour flux distribution, with the flux approximately evenly spread around the tip of the wire electrode. As shown in Figure 8, there is a small region immediately below the wire electrode tip in which a local temperature minimum occurs on axis. However, it only extends about 0.3 to 0.4 mm; it is not clear why this is smaller than that found in the results presented here. It may be a consequence of the different treatment of the boundary conditions at the interface between the plasma and wire electrode.

The mass conservation equation (9) was replaced by \( \nabla \cdot (\rho \mathbf{v}) = 0 \), and the influence of the metal vapour influx on the plasma flow was taken into account by introducing the velocity of the metal vapour at the interface between the wire electrode and the plasma as a boundary condition in the momentum conservation equation.

### 3.4.3 Discussion

Consideration of the work of Schnick et al. [9, 10] and Haidar [11], and the results presented here, indicates that there are two distinct mechanisms that can lead to a local temperature minimum, and decrease arc temperature. The increased radiative emission from metal vapour can lead to a temperature minimum that is more likely to occur well below the wire electrode tip, while the flux of metal vapour from the wire electrode can lead to a local temperature minimum immediately below the tip. The former mechanism is favoured by higher currents and the use of a wire electrode made of steel or iron rather than aluminium, while the latter is favoured by a downward flux of metal vapour. Both mechanisms lead to a temperature decrease in all regions of the arc.

Measurements of GMAW arc temperatures have been made for steel electrodes at relatively high arc currents, so it is not possible to confirm these arguments. Nevertheless, measurements made at different axial positions by Zielinska et al. [8] (see Figure 1) and Valensi et al. [7] for high-current arcs with steel electrodes show that the temperature minimum occurs at all positions measured, and becomes deeper at positions closer to the wire. It should be noted, however, that the distance from the wire in these measurements is uncertain owing to droplet formation and detachment. Nevertheless, the results are consistent with both increased radiative emission and the downward flux of metal vapour having an influence.

### 4 Conclusions

We have investigated, using a three-dimensional computational model that includes vaporization of the electrodes self-consistently, the effects of metal vapour on the arc temperature for a 95 A arc with aluminium electrodes, typical of that used for welding thin
sheets of aluminium. The results indicate that (1) both the increased radiative emission due to the presence of metal vapour, and the effects of the strong flux of relatively-cold vapour from the wire electrode, are important in the overall decrease in the arc temperature, but (2) the local minimum in arc temperature near the arc axis is a consequence of only the second effect.

By considering the modelling results in literature, it has been shown that higher arc currents, and the use of iron or steel electrodes, can lead to the formation of a local temperature minimum due to the strong radiative emission from metal vapour. It is therefore concluded that, depending on the arc current and the electrode metal, local temperature minima can be caused by both the flux of vapour from the wire electrode, and radiative cooling.

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