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Comparison of temperature and composition measurement by spectroscopic methods for argon–helium arc plasma

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ABSTRACT

Three different spectroscopic methods were used to calculate the temperature and composition distribution of argon–helium arc plasma—the Fowler–Milne method, the two-line intensity correlation method and the Boltzmann plot method. Experimental errors, including random errors and systematic errors, were analyzed in detail to comparing the accuracy of different methods. Due to the large differences of physical characteristics between argon and helium, there were limited reports on the measurement of temperature and composition distribution in argon–helium arc plasma. To this end, The Fowler–Milne method and the Boltzmann plot method were modified in this paper. Three spectroscopic methods were compared with other's simulation result and showed good agreement with each other, except the Boltzmann plot method which had partly distinction. Through comparison and analysis of error bar in those methods, it was found that both the Fowler–Milne method and the two-line intensity correlation method had less error than the Boltzmann plot method, while the Fowler–Milne method, which is irrelevant to atomic transition probabilities and experimental apparatus calibration, had the minimum error.

1. Introduction

Emission spectroscopy, which does not disturb the arc plasma, is a very effective way to investigate the plasma property. And most of the spectral measurement techniques have been applied to determine the temperature in single gas arc plasma [1,2]. However, it seems that the temperature measurement of arc plasma presented by many researchers have mutually contradictory results, as indicated by Lancaster [3]. For example, the measured temperature using the Fowler–Milne method is higher than those using the Boltzmann plot method. Those groups using a relative or an absolute intensity method had considerable disagreement results, while the Fowler–Milne spectroscopic technique obtained consistent values [4]. Moreover, the presence of additional gas causes demixing in most cases, which means temperature and gas composition changes with position. The existence of demixing significantly complicates the measurement for multi-element arc plasma. Hence, most of the accepted methods need to be modified for applying in multi-element arc plasma. In this paper, different spectroscopic methods were introduced and then the temperature and gas composition (mole fraction of argon in arc plasma) distribution were compared among those methods in the mixture of argon–helium arc plasma.

Due to the complexity of measurement in multi-element arc plasma, only few researchers measured its temperature and gas composition distribution in gas tungsten arc welding (GTAW) using mixed gas. Song et al. [5,6] used absolute intensity of Ar I, Hα and N I line, to determine temperature and gas composition in argon–hydrogen arc plasma and argon–nitrogen arc plasma. The result showed that hydrogen concentrate in the center of the arc plasma. Hiraoka [7,8] used a two-line intensity correlation method to measure temperature and composition distribution in the multi-element arc plasma. It involved the measurement of the relative intensity of Ar I and Ar II lines or Ar I and H I lines to obtain temperature distribution of Ar–He or Ar–H_2 mixed-gas tungsten arc plasma, and find the helium concentrate on the axis of arc. Murphy [9] used a modified Fowler–Milne method to measure the radial profiles of temperature and gas composition of free-burning arcs in mixtures of argon and nitrogen. The results demonstrate that the occurrence of demixing depending on the relative concentration of argon and nitrogen. These methods are used in different gas mixtures in different experimental conditions, so they are difficult to compare with each other.

Due to the physical characteristic between argon and helium differs largely, i.e., the first ionization energy of helium is much

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larger than that of argon, the density of helium is much lighter than that of argon, there exist large differences in ionization degree and complicate spectra chosen. There are thus limited reports on measuring the temperature and composition for the mixture of argon and helium. Only Hiraoka [7,10] used the two-line intensity correlation method to measure the temperature and composition distributions in the argon–helium arc plasma of 100 A. It is interesting to compare with other spectroscopic methods and analyze the error distribution.

In this study, we will use a spectrometer system to measure spectral intensity distribution, and then use three different spectroscopic methods to obtain the temperature and composition of arc plasma with the mixture of argon–helium in GTAW. Firstly, the Fowler–Milne method was applied in the mixture of argon–helium arc plasma. Though Murphy [9] used this method in argon and nitrogen mixtures, they have similar physical property and got the similar normal temperature. However, there were problems existing in argon–helium gas mixture. From the perspective of first ionization energy and density, there are wide gap between argon and helium, as a result, their normal temperatures are quite different. In fact, the normal temperature of He I is above the temperature of arc plasma, and the maximum emission coefficient could not be measured. Nevertheless, the Fowler–Milne method requires that value, we chose Ar I and Ar II spectral lines in the study since their maximum emission coefficient could be obtained. Then, the two-line intensity correlation method and the Boltzmann plot method were used for temperature and composition measurement under the identical conditions. Meanwhile the experimental errors, including random errors and systematic errors, were thoroughly analyzed for each method. Furthermore, a comparative investigation was carried out for their respective temperature and composition results between the following spectroscopic methods: a) the Fowler–Milne method; b) the two-line intensity correlation method; c) the Boltzmann plot method, and others' simulation result [11], and they are also analyzed according to their error distribution.

2. Experimental system

The experimental system mainly contains two parts. One is arc plasma source, which is used to produce arc plasma; the other is a spectrum acquisition system, which is used to obtain spectral intensity of arc plasma.

2.1. Arc plasma source

In the experiment, a direct current (DC) arc was generated in the gas mixture of argon and helium at atmospheric pressure by welding power supply (DA300P-type, OTC Corporation, Japan). The arc freely burned between a tungsten cathode and a stationary water-cooled copper plate anode.

A 2.4-mm-diameter tungsten electrode adding 2% ThO_2 with a cone angle of 60° was employed as cathode. A water-cooled copper-plate vertically located below the cathode was employed as anode. Arc distance, defined as the distance from the tungsten electrode tip to copper-plate surface, is 5 mm. The mixture of argon (50% in volume) and helium (50% in volume) was used as the shielding gas feeding from the cathode nozzle with a flow rate of 10 L min^{-i}, and the current was set at 200 A.

2.2. Spectrum acquisition system

The spectrum acquisition system consists of a single lens system, a motion control device and a spectrometer. Radiation from the arc plasma was imaged by a single lens system onto an imaging screen at a magnification of 2:1. The convex lens (focal length is 0.3 m) was fixed 0.45 m away from the arc, thus the parallel-ray projection condition assumed in the Abel inversion can be approximately satisfied. A light aperture was employed to limit light from the arc for obtaining adequate spatial resolution. In the image screen which was places 0.9 m away from the lens, an optical fiber (P400-UV-SR, Ocean Optics, USA) was mounted on a motion control device which can be moved in both horizontal and vertical directions. The internal diameter of the optical fiber is 0.4 mm and thus the scanning step along the horizontal direction was determined as 0.4 mm. Light along the chord of arc 1 mm below the cathode tip was transmitted by the optical fiber to the spectrometer (HR-4000UV-NIR, Ocean Optics, USA) of 3648 pixels with a spectral range from 200 to 1100 nm. The spectroscopic acquisition system is schematically shown in Fig. 1.

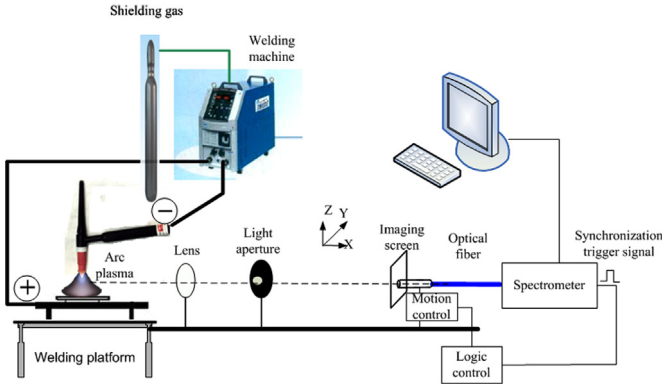

Fig. 1. Spectroscopic acquisition system for arc plasma.

3. Measurement of temperature and composition distribution by different methods

Since temperature and gas composition could not be measured directly, they are derived from different spectroscopic methods which need the value of emission coefficient, and the measurements are line-of-sight integrated intensities, the distribution of emission coefficients must be reconstructed. This is accomplished by means of an Abel inversion, provided the plasma is cylindrically symmetric and optically thin. For Abel inversion, the measured intensity of the spectral line was corrected by subtracting the corresponding continuum radiation intensity first. Then, the side-on measured spectral line intensity profiles were symmetrized, noise filtered, and the Bockasten method [12,13] was used to convert intensity to emission coefficient. Since this experimental system was not calibrated to the absolute intensity, this emission coefficient is relevant to the experimental system. Hence, it is a relative emission coefficient.

The line emission coefficient ε_{nm} of a transition from level m to lower level n of species j in plasma is given by [3]

$$\varepsilon_{nm} = \frac{hc}{4\pi\lambda_{nm}} g_m A_{nm} \frac{n_j(T)}{U_j(T)} \exp\left(-\frac{E_m}{kT}\right) \quad (1)$$

where $n_j(T)$ and $U_j(T)$ are respectively the number density and the partition function of the species j, E_m and g_m are the energy and statistical weight of the upper level, A_{nm} is the transition probability, λ_{nm} is the wavelength of the radiation emitted, and c, h, and k are respectively the speed of light in a vacuum, Planck's constant, and Boltzmann's constant. Hence, the intensity of emission from a single spectral line depends on the temperature T and the number density n_j of the emitting species. If the plasma is in local thermal equilibrium (LTE), and only one chemical element is present in the