Supersonic Plasma Jets of Different Gases in Low-Pressure Environment

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***Abstract*— A low-power dc arc plasma generator with regeneratively cooled or natural-radiation-cooled anode is used to produce supersonic plasma jets of pure helium, argon, hydrogen, nitrogen, hydrogen–nitrogen mixture, and helium–nitrogen mixture in a vacuum chamber. Plasma plume images of different characteristics were observed, and are discussed briefly along with the measurement and analysis results.**

***Index Terms*— Arc-heated jet (arcjet), supersonic plasma plume.**

ONE kind of nontransferred dc arc plasma torch uses electrodes with no water cooling, and the anode temperature could change with the nozzle structure, input power, gas type, and feeding rate. Some of these torches, called arc-heated jet (arcjet) thrusters, are used in space propulsion; 2-kW class hydrazine arcjet thrusters have been successfully applied to many satellites since the 1990s [1]. The propellant is arc heated, and then the conversion of thermal energy into directed kinetic energy occurs in the anode/nozzle. In principle, arcjet is capable of operating on a variety of propellants, to meet space mission requirements.

Pure He, Ar, H_2, N_2, H_2/N_2, and He/N_2 mixtures with different volume ratios were used as propellants in an arcjet thruster set in a vacuum chamber. For pure He and He/N_2 mixtures, natural-radiation-cooled nozzle (N nozzle) of 0.6-mm throat and 8.9-mm exit dia was used, and regeneratively cooled nozzle (R nozzle) of 0.7-mm throat and 11-mm exit dia was used for the other propellants. Images of the plasma plume (Fig. 1) were taken using a video camera at the beginning stage of the firing to avoid the nozzle emission.

The various propellants demonstrate quite different arc and plume characteristics. After the operation stabilized at a high nozzle temperature, the arc voltage always showed decreased characteristics with increasing arc current, regardless of the working gas type and feeding rate. However, in the case of argon plasma, the arc voltage was lower than 38 V and the nozzle temperature was generally lower than 900 K because of the low ionization energy and low heat-conductivity coefficient of argon. On the other hand, the arc voltage can increase to 150 V, and the nozzle temperature could be higher than 1500 K for hydrogen plasma.

The He plume was injected into the chamber at 1 Pa and other pure gases into 10 Pa environment. The N_2 plume [Fig. 1(d)] expanded to a much broader area than the helium plume injected into one-order lower pressure, but the mixture plumes with nitrogen showed similar characters as those of the other gases in the mixture. These behaviors reflect the effects of gas media on arc characteristics, flow process, energy conversion, heat transfer, and distribution of losses, which result in different exit gas parameters. Some of the phenomena agree with the numerically predicted results [2], which showed that the nitrogen jet has the highest exhaust heat-loss fraction among all the pure and mixture gases. Owing to the lower mass flow and high viscosity of helium, the low Reynolds number flow results in low Mach number at the exit and an underexpanded jet, which continues to expand in the exhaust chamber, exhibiting a broader outline [Fig. 1(a)] compared with the Ar plume [Fig. 1(b)].

All of the plasma plumes in Fig. 1 are supersonic with gas temperatures lower than 3000 K (except in pure nitrogen where it could be higher), according to the experimental estimation and numerical simulation results. Unlike ordinary supersonic flow in higher pressure environment (over 100 Pa), reflected and compression shock waves could not be observed in pictures here, due to the very thick boundary layer and compression zone caused by the rarefied gas effect. The pure gas plumes show colors characteristic of the optical emission lines of those gases, but the gas mixtures show colors that are not typical of the constituent gases. This might be caused by interaction between gas species, also nonequilibrium effects, and could be worthy of further investigation.

In summary, arc-heated plasma plumes of various gas types showed quite different image characteristics. This is the result of a complicated combination of factors. Although they are all in the supersonic flow state, no shock waves could be observed due to the rarefied gas effects.

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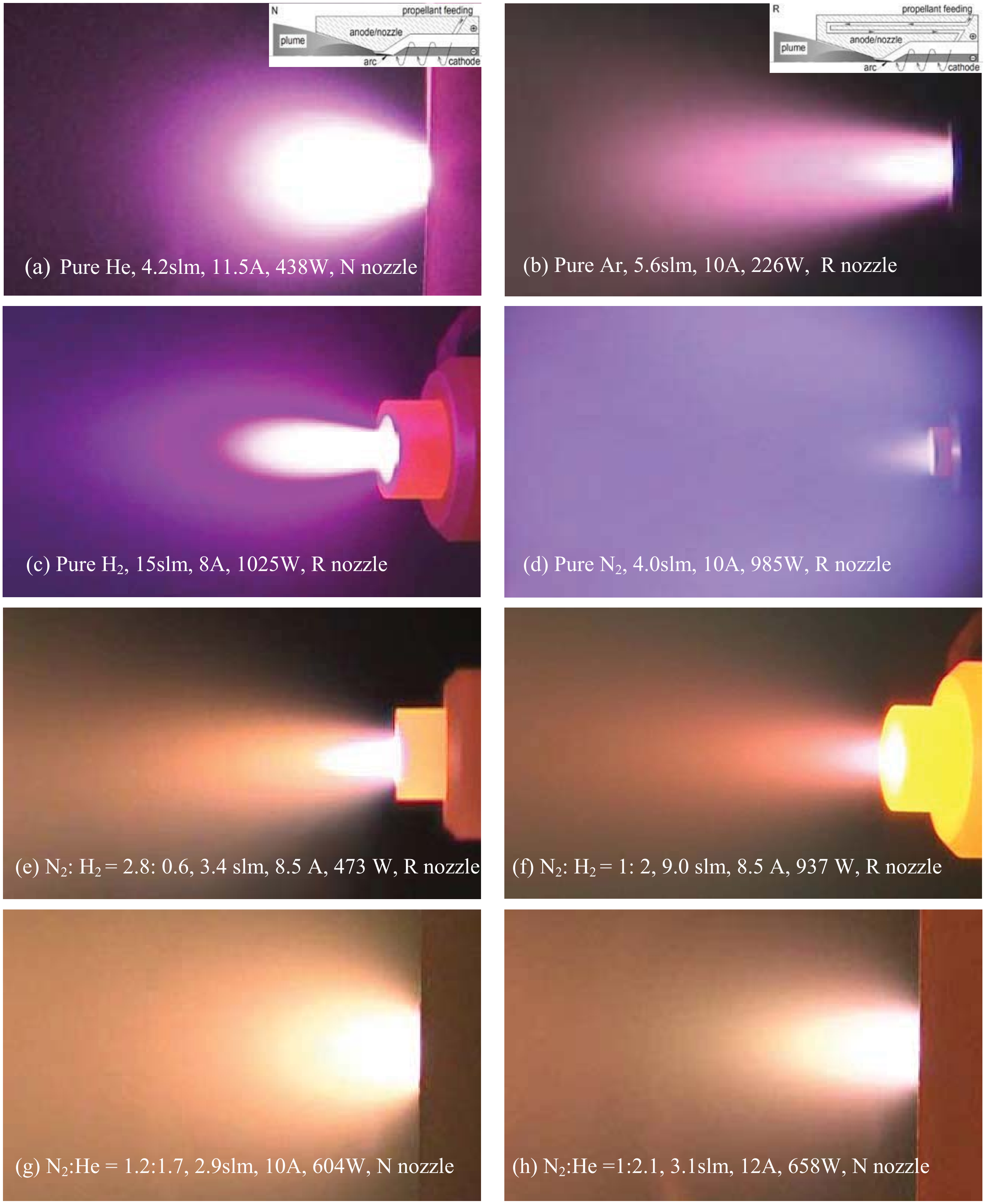

Fig. 1. Photographs showing the appearance of the low-power plasma plumes. (a) Pure He, 4.2 slm, 11.5 A, 438 W, N nozzle. (b) Pure Ar, 5.6 slm, 10 A, 226 W, R nozzle. (c) Pure H_2, 15 slm, 8 A, 1025 W, R nozzle. (d) Pure N_2, 4.0 slm, 10 A, 985 W, R nozzle. (e) N_2:H_2 = 2.8:0.6, 3.4 slm, 8.5 A, 473 W, R nozzle. (f) N_2:H_2 = 1:2, 9.0 slm, 8.5 A, 937 W, R nozzle. (g) N_2:He = 1.2:1.7, 2.9 slm, 10 A, 604 W, N nozzle. (h) N_2:He = 1:2.1, 3.1 slm, 12 A, 658 W, N nozzle.