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Letter

Producing ultra-high-speed nitrogen jets by arc heating in a low-pressure chamber

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HIGHLIGHTS

- Pure nitrogen was accelerated with a low-power arc-heater of novel structure.
- The jet flow can reach very high speed around 7 km/s.
- A bypass-exhaust for cool boundary layer at end of the throat plays an important role.

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ABSTRACT

Pure nitrogen gas was heated with direct current arc, at input powers from several hundred W to over 5 kW, and then injected through a nozzle into a chamber at 1 or 10 Pa pressure, with the purpose of accelerating the gas to very high speed around 7 km/s. Various structures of the arc generator and gas expansion nozzle were examined. Results show that bypass exhausting of the boundary layer before it enters the nozzle divergent section can greatly increase flow speed of the jet, thus it might be possible to use nitrogen as a working gas in high speed gas dynamic test facilities.

Non-transferred direct current (dc) arc heaters, extremely high temperature gas heaters or plasma jet generators are widely used in materials processing [1,2], space thruster application [3,4] and wind-tunnel test facilities [5,6] for high speed flight. One feature of these installations might be the production of high speed, high total-temperature jet, which may have various significance in different applications. Nitrogen is a popular working gas for arc heating application in industry usages. However, it is quite difficult to be accelerated to very high flow velocities by arc heating and nozzle expansion, to be used for space thruster and special high speed flow testing applications. Thus, few research results have been reported for nitrogen propellant arcjet thrusters [7], compared with hydrogen, ammonia and helium propellants, etc. Generally, specific impulse of nitrogen arcjet is much lower than 300 s [7], and its maximum axial flow velocity near the nozzle exit center is around 4 km/s [8].

Flow in the small nozzles used in low-power arcjets demonstrates much more complicated phenomena and energy conversion mechanism than those in the normal rocket, although their working principles are basically similar. Arcjets are also quite different in working principle as other electric thrusters like the ion or Hall engine. In testing of the arcjets in low-pressure environments, the propellant flow rates are much higher compared to other kinds of electric thrusters. This causes difficulty in keeping a high vacuum level in the simulation facility chamber and in reflecting the real performance which an arcjet would have in space propulsion. At the same time, it is difficult to limit the gas feeding simply by reducing the diameter of throat because of the relative thick boundary layer in the small flow passage [9].

It is the purpose of this work to study ways of producing very high speed nitrogen jets, to see if they might be useful in certain special applications. In these experiments, pure nitrogen, heated by an electric arc, was expanded through a small nozzle and issued into a low-pressure chamber as a high speed jet. The construction of the heater-nozzle combination and the operating conditions were varied to see their effects on the jet performance when injected into different environment pressures. An effort was made to relieve the effects of the thick boundary layer: a lateral bypassing exhaust technique was adopted at the throat exit section, with the purpose of producing a high speed nitrogen jet in the exhaust chamber.

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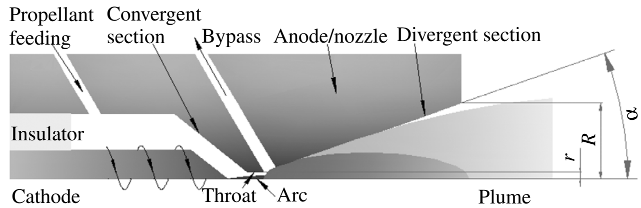

Fig. 1. The schematic diagram of arc heater (Structure D).

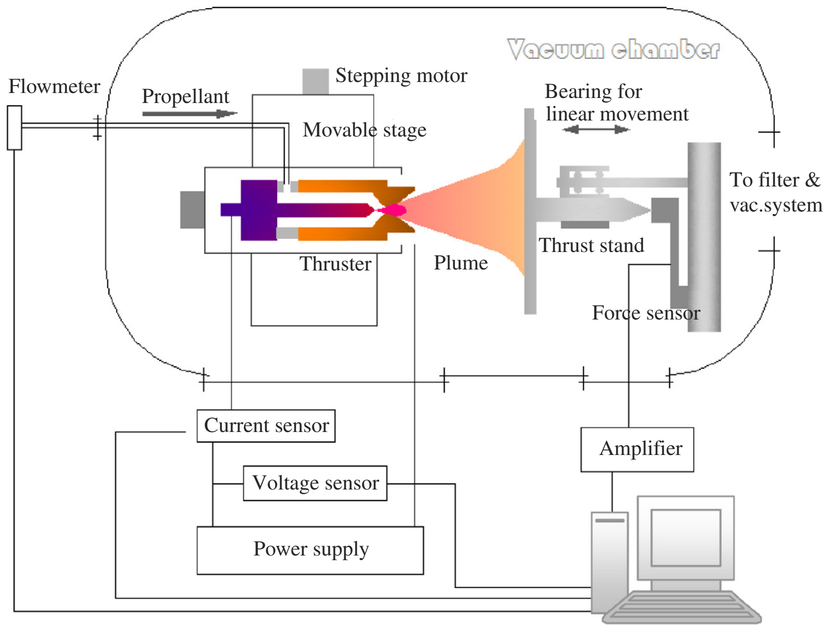

Fig. 2. Schematic drawing of the facility.

Four structures of anode/nozzle were studied: A, throat dia. 0.7 mm, expansion half-angle 20°, expansion area ratio 204; B, throat dia. 0.6 mm, expansion half-angle 20°, expansion area ratio 220; C, throat dia. 0.6 mm, expansion half-angle 15°, expansion area ratio 220; D, throat dia. 1.1 mm, expansion half-angle 20°, expansion area ratio 330, with a bypass exhausting structure. Schematic diagram of the arc heater D is shown in Fig. 1. Pure nitrogen was used as the working gas. The experiments were run within the range of stable operation of the arc and where long run time could be maintained without burning out or damage of the nozzle. This limits the range of arc current to an order of 10 A for the nozzle A, B and C, and 50 A for nozzle D, corresponding gas flow rates 50 mg/s and 208 mg/s, respectively. In structure D, an annular slit of about 0.4 mm width is opened at the end of the throat section, connected to the Roots and mechanical pumps. This arrangement provides means to pump out the cooler, higher-density gases near the wall, so that the hotter gas at the center of the electric arc can expand more fully in the divergent portion of the nozzle. The diverted flow rate was measured by a flow meter.

Figure 2 shows the schematic drawing of the facility consisting of a vacuum chamber, 2 m diameter by 4 m long, ultimate vacuum 10^{-4} Pa. Two sets of vacuum pumps, one with a Roots blower and a mechanical pump for higher operational flow rates at ∼10 Pa chamber pressure, another with an additional diffusion pump with maximum exhausting rate of 30 000 L/s and molecular pumps of total 7000 L/s exhausting rate for lower flow rates at ∼1 Pa. The chamber pressure was detected with a capacitance gauge with measuring range of 0.01 Pa–133 Pa. The chamber pressure shows a rapid change during arc ignition or working parameters adjustment, but these fluctuations are much smaller than in the situation when small chamber and high gas flow rate are used, and the present data were taken under conditions where the pressure was steady. The arc heater is mounted on a movable table driven by stepping motors. The produced thrust is measured indirectly by the impulse method [10]. The mass flow rate, arc current and voltage, pressures, etc. are measured by transducers and were collected on a computer. From the measured parameters, the specific power input, specific impulse and thrust efficiency are calculated [9]. The specific impulse actually reflects the average axial speed of the exhausting jet.

For non-transferred dc-arc gas heater of a given structure, the range of operating parameters for stable operation and negligible erosion of the electrodes is not very wide. And to keep a nearly constant environmental pressure in the vacuum chamber with a given set of pumps, the flow rate of the gas heater is basically fixed. Thus the data presented are rather limited in range. Data for the different nozzle structures and at 10 or 1 Pa exhaust pressures are given in the same diagrams to see the differences more clearly.

Figure 3 shows the voltage–current characteristics of the heaters at 10 Pa and 1 Pa exhaust pressure. The arc voltage always rises with increasing flow rate. Nozzle D has much higher arc voltage, because it uses much higher flow rate and arc current, and cannot be directly compared with the other nozzles. At the same vacuum chamber pressure of 1 Pa and same flow rate and arc current, heater C has significantly higher arc voltage than heater B. This could be caused by different arc anode root attachment positions in the two heaters with their different nozzle configuration.

The thrust produced by the exhausting jet is related to the gas velocity and the flow rate, the measured results are shown in Fig. 4. For nozzle D, the flow rate shown is the value of the total flow subtracted by the laterally exhausted flow, since the latter