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Air plasmas sustained by repetitive high-voltage nanosecond pulses: fundamental kinetics and aerodynamic applications[1]

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The paper reviews the recent studies of highly efficient generation of weakly ionized plasmas and their applications to supersonic/hypersonic flight. Plasmas can be used simply as means of delivering energy (heating) to the flow, and also for electromagnetic flow control and magnetohydrodynamic (MHD) power generation. Plasma and MHD control can be especially effective in transient off-design flight regimes. In cold air, nonequilibrium plasmas must be created, and the ionization power budget determines the design and performance envelope of plasma/MHD devices. The minimum power budget is provided by electron beams or repetitive high-voltage nanosecond pulses, and the paper describes theoretical modeling of those plasmas. The models include coupled equations for non-local and unsteady electron energy distribution function (modeled in forward-back approximation), plasma kinetics, and electric field. The modeling is in good agreement with experimental studies of quiescent air plasmas sustained by 2-nanosecond, 5 kV/cm, high (100 kHz) repetition rate pulses, where the average energy cost per electron was found to be about 100 eV, two orders of magnitude lower than in quasineutral DC and RF plasmas. Detailed investigations of the plasma dynamics revealed a critical role of the cathode sheath that was found to take up most of the peak voltage applied to the electrodes. The extremely high E/N, much higher than the Stoletov's field at the Paschen minimum point, results in a very high ionization cost in the sheath. In contrast, the E/N in the quasineutral plasma is closer to that associated with the Stoletov's point, resulting in a near-optimal electron generation. The positive space charge in the sheath and its relatively slow relaxation due to the low ion mobility was also found to result in reversal of electric field direction in the plasma at the tail of the high-voltage pulse. Experimental studies at Princeton University have also successfully demonstrated stable diffuse plasmas sustained by repetitive nanosecond pulses in supersonic air flow, and for the first time have demonstrated the existence of MHD effects in such plasmas. As one potential application, cold-air hypersonic MHD devices are shown to permit optimization of scramjet inlets at off-design Mach numbers while operating in self-powered regime.

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