Commun. Comput. Phys.
doi: 10.4208/cicp.090615.140316a

Vol. **20**, No. 5, pp. 1424-1442
November 2016

Numerical Study of Nanosecond Pulsed Plasma Actuator in Laminar Flat Plate Boundary Layer

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Received 9 June 2015; Accepted (in revised version) 14 March 2016

Abstract. Nanosecond (ns) pulsed dielectric barrier discharge (DBD) actuator in a laminar flat plate boundary layer is investigated numerically in an attempt to gain some new insights into the understanding of ns DBD actuation mechanism. Special emphasis is put on the examination, separation and comparison of behaviors of discharge induced micro shock wave and residual heat as well as on the investigation of response of external flow to the two effects. The shock wave is found to introduce highly transient, localized perturbation to the flow and be able to significantly alter the flow pattern shortly after its initiation. The main flow tends to quickly recover to close to its undisturbed state due to the transient nature of perturbation. However, with the shock decay and final disappearance, another perturbation source in the vicinity of discharge region, which contains contribution from both residual heat and shock, becomes increasingly pronounced and eventually develops into a perturbation wave train in the boundary layer. The perturbation is relatively weak and may not be a Tollmien-Schlichting (TS) wave and not trigger the laminar-turbulent transition of boundary layer. Instead, it is more likely to manipulate the flow stability to achieve the strong control authority of this kind of actuation in the case of flow separation control. In addition, a parametric study over the different electrical and hydrodynamic parameters is also conducted.

AMS subject classifications: 35L65, 76L05, 76N20, 76N25

Key words: Dielectric barrier discharge actuator, nanosecond voltage pulse, shock wave, boundary layer, flow control.

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1 Introduction

Dielectric barrier discharge (DBD) actuator excited by high voltage pulse with rise and decay time of nanosecond (ns) order, as sketched in Fig. 1, is being investigated intensively as a potential active flow control means. When pulse voltage supplied to the upper

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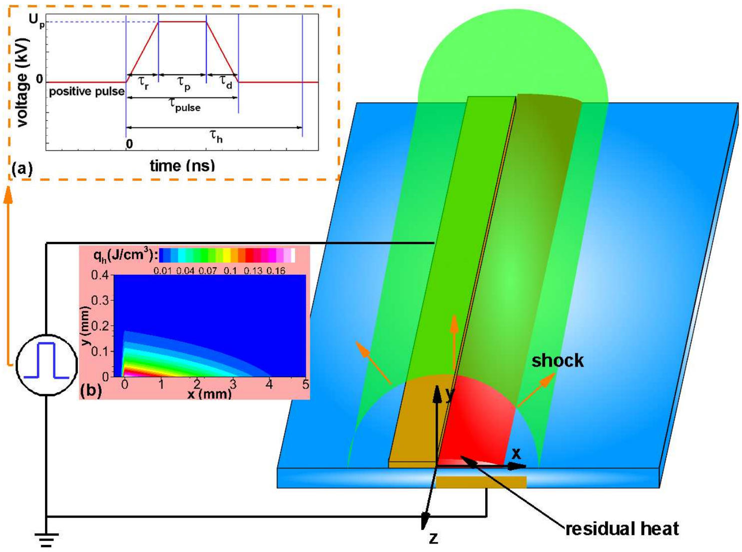

Figure 1: Schematic of a plasma actuator excited by a nanosecond pulse voltage with inserted plot (a) showing the shape of voltage pulse and plot (b) depicting the predicted heating energy density.

electrode of actuator, which is mounted on a dielectric layer and exposed to air, exceeds the breakdown threshold of air particles, the near surface air over buried electrode will weakly ionize, generating so-called plasma which appears blue in experiment. Accompanying the discharge procedure is the conversion of part of electrical energy into gas heating within the discharge region in less than $1\mu s$, which is too short for the heated gas to expand. Hence, the pressure also rises quickly and appreciably in the heated volume and the resulting pressure jump causes the generation of a shock wave.

This type of actuator has been applied to a wide range of flows from subsonic [1–6] to supersonic regimes [7] and demonstrated flow control potential. The mechanism whereby the ns DBD actuator achieves control authority is believed to be related to the thermal effect of plasma discharge and the resulting two flow features, i.e. the outward-expanding shock wave and residual heat remaining in the discharge region, as shown in Fig. 1. However, the two features occur on disparate temporal scales and exhibit different characteristics. The shock wave travels relatively fast through flow and usually decays to an acoustic perturbation hundreds of microseconds after its initiation. By contrast, the residual temperature will take much longer time to relax to the ambient condition and has a characteristic time which may be several orders of magnitude different from that of the shock wave. As the two effects interfere with the external flow in distinct ways and function under fundamentally different mechanisms, either of them or both in combination may play the dominant role in a specific flow control case, which may depend on the nature of main flow and other factors. The working principle of ns plasma actuator is different from that of traditional alternating current (AC) driven actuator. The