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Hypersonic flow control of shock wave/turbulent boundary layer interactions using magnetohydrodynamic plasma actuators

Hao JIANG

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Physical Model

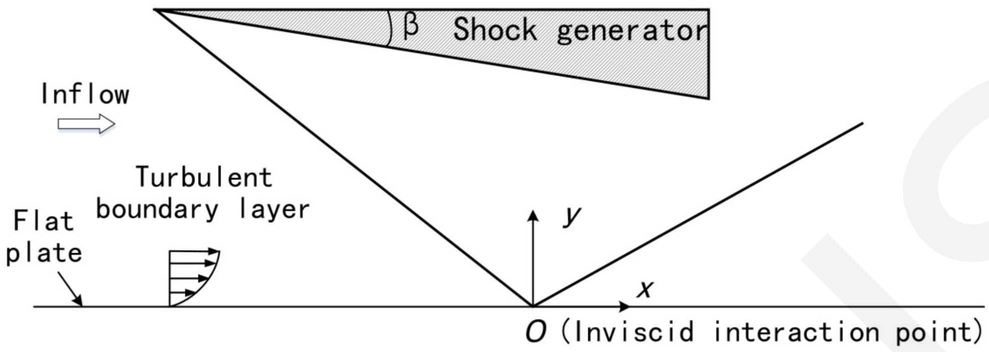

Fig. 1 Baseline configuration

Table 1 Reference conditions for baseline flow

Parameter	Value
Ma	5.0
T_∞	68.33 K
T_w	300 K
P_∞	4006.8 Pa
Re/m	3.6737×10^7

- **The physical model used here adopts a configuration from Schülein's experiment (2006), specifically the interactions between oblique shock produced by a 14° wedge and a turbulent hypersonic boundary layer.**

Actuator Model

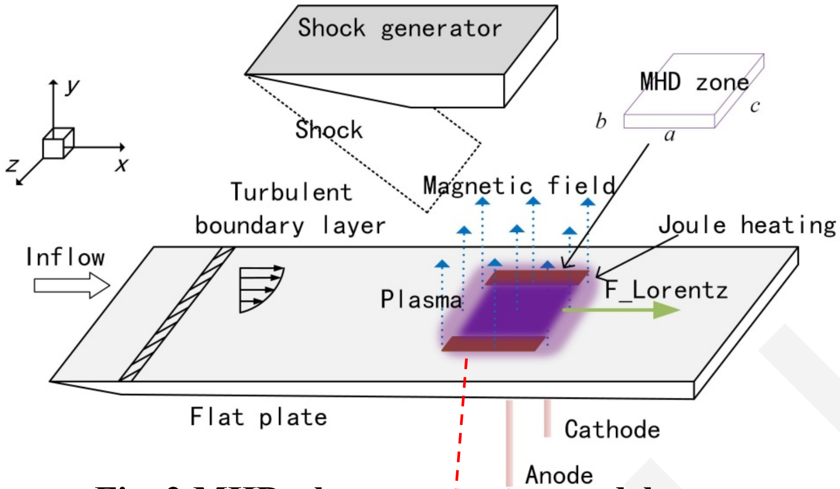

Fig. 2 MHD plasma actuator model

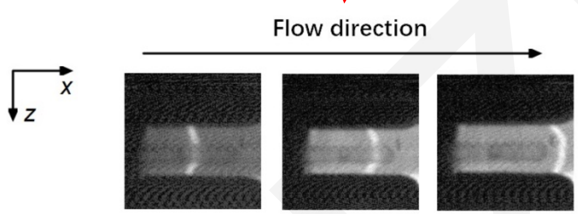

Fig. 3 (a) High-speed photographs of the arc movement downstream at B = 0 Tesla in Zaidi's experiments

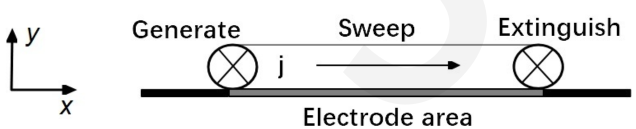

Fig. 3 (b) 2D schematic diagram of arc movement

- **The external magnetic field is applied in +*y* direction and the external electrical field is applied in +z direction.**
- **On the basis of experimental results and the assumptions referred in the paper, an actuator was incorporated in the fluid using time-mean source terms. The momentum exchange and Joule heat in the MHD zone from the actuator were then semi-empirically modeled as a steady and uniform heat source and a magnetic body-force term in the momentum and energy equations, respectively.**

Overview of MHD Control

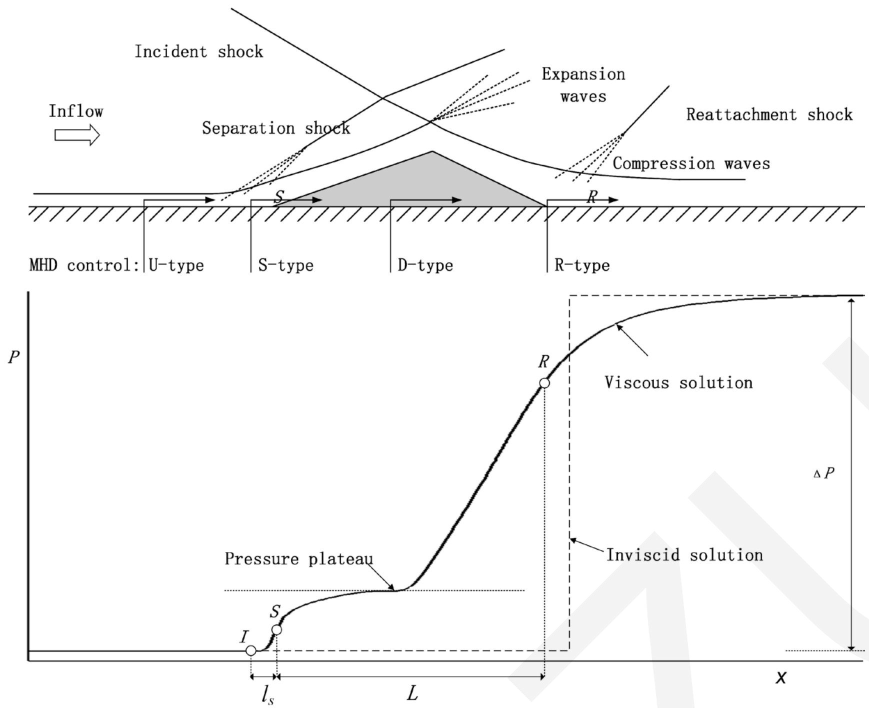

Fig. 4 Four types of MHD control positions of incident shock-induced turbulent boundary layer separation and wall static pressure

- **U-type: MHD interaction is located upstream of where the separation point would have been without control;**
- **S-type: MHD interaction is used across the separation point without control;**
- **D-type: MHD interaction is inside the separation bubble and starts from the uncontrolled separation point;**
- **R-type: MHD interaction is around the reattachment point.**

MHD Parameters

Original MHD Interaction Parameters

$$S=\frac{\sigma B^2 L_{\mathrm{MHD}}}{(1+\Omega_e\Omega_i)\ \rho U_\infty}$$

$$S'=\frac{\sigma B^2 L_{\mathrm{MHD}}}{\rho U_\infty}k$$

$$S_\tau=\frac{\sigma B^2 L_{\mathrm{MHD}}}{\rho U_\infty \sqrt{C_f/2}}=\sqrt{2/C_f}\times S$$

$$S'_\tau=\frac{\sigma B^2 L_{\mathrm{MHD}}}{\rho U_\infty \sqrt{C_f/2}}k=\sqrt{2/C_f}\times S\times k$$

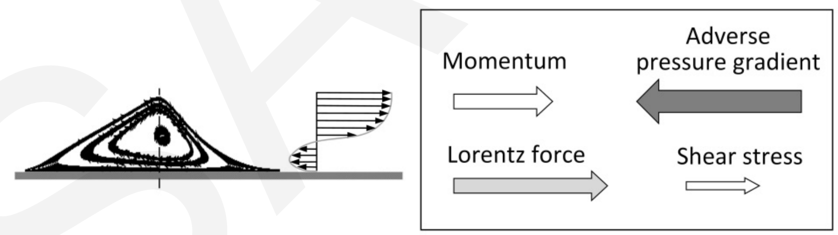

Fig. 5 The force balance of STBLI with MHD control in the x direction

$$\frac{\partial}{\partial x}\left(\rho u^2\right)=-\frac{\mathrm{d}p}{\mathrm{d}x}+\frac{\partial \tau}{\partial y}+f_x.$$

Newly Proposed MHD Interaction Parameter

$$S_{\Delta P}=-\frac{\sigma EBL}{\Delta P}$$

To include the main factor in the STBLI

MHD Control Types

- **Control Types**

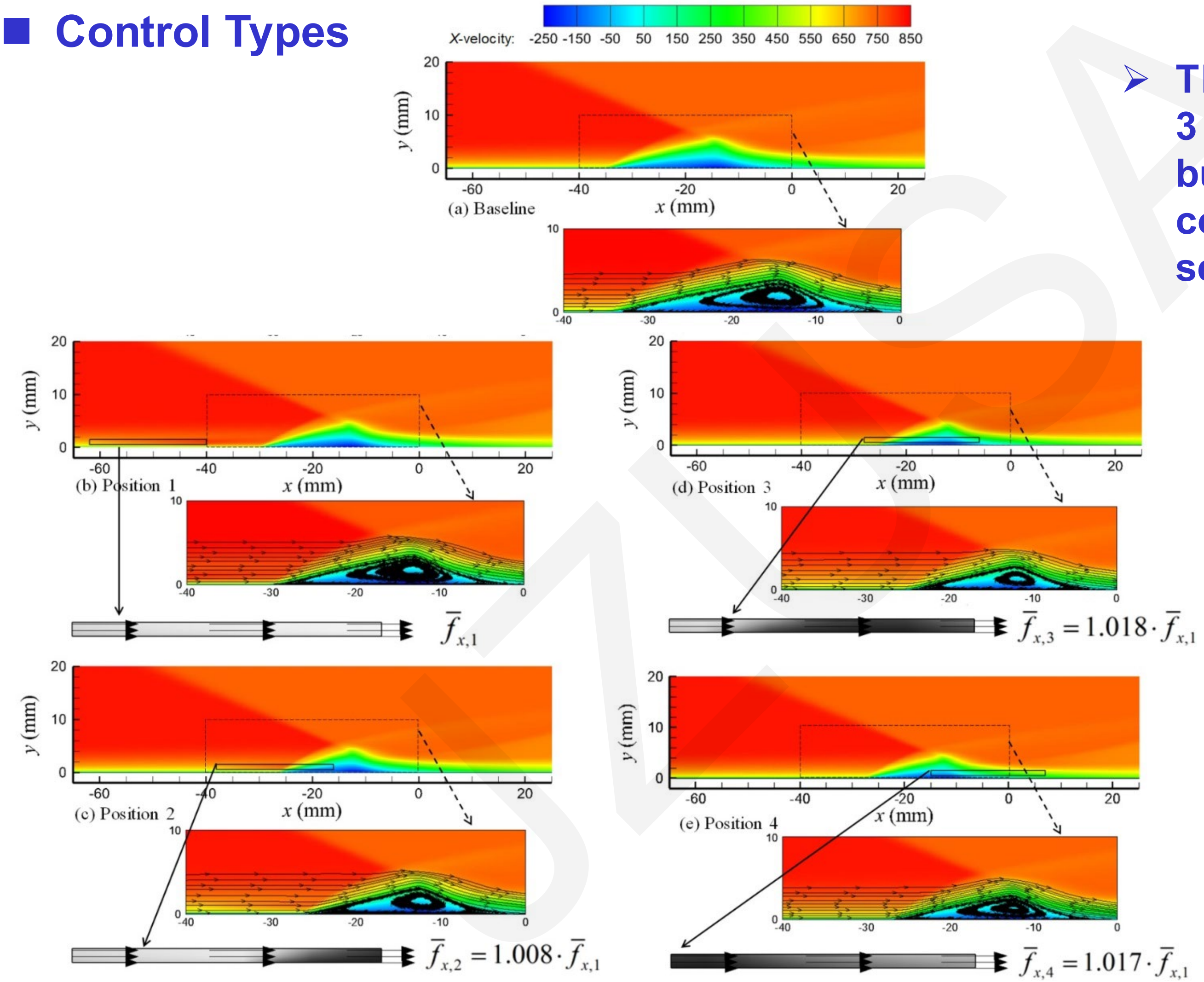

Fig. 6 *X*-velocity contour of baseline and four types of MHD control cases.

- **The MHD zone in position 3 is inside the separation bubble. This D-type MHD control shows the largest separation reduction.**

MHD Control Types

Wall Distance

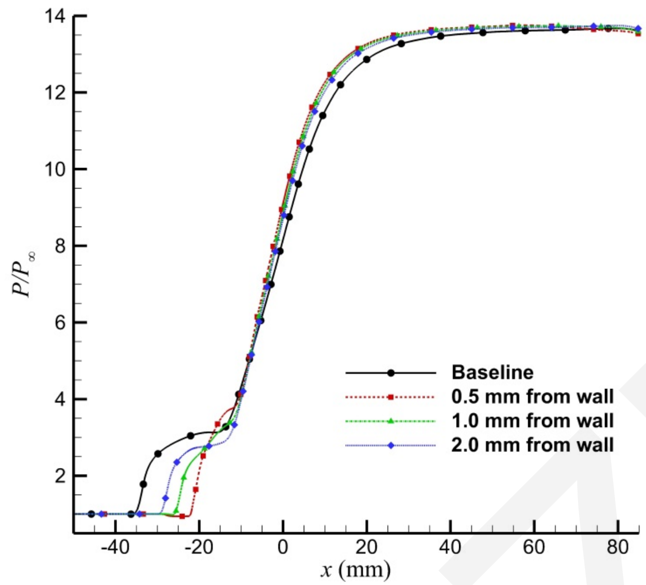

Fig. 7 Wall static pressure distributions of baseline and MHD control at three different wall distances

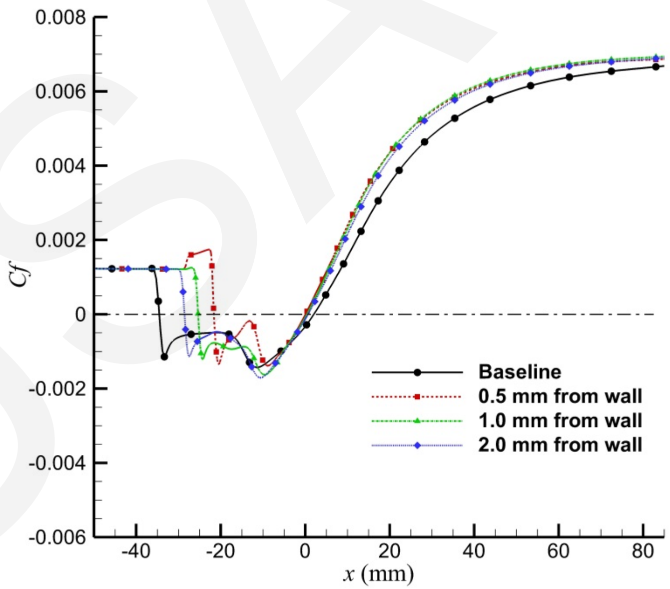

Fig. 8 Wall skin friction coefficient distributions of baseline and MHD control at three different wall distances

- Moving the plasma closer to the wall and deviating from freestream flow results in increased separation control. This shows that plasma actuation works best in the lowest-velocity region of the BL.

Effect of MHD Parameters

■ Joule heating effects

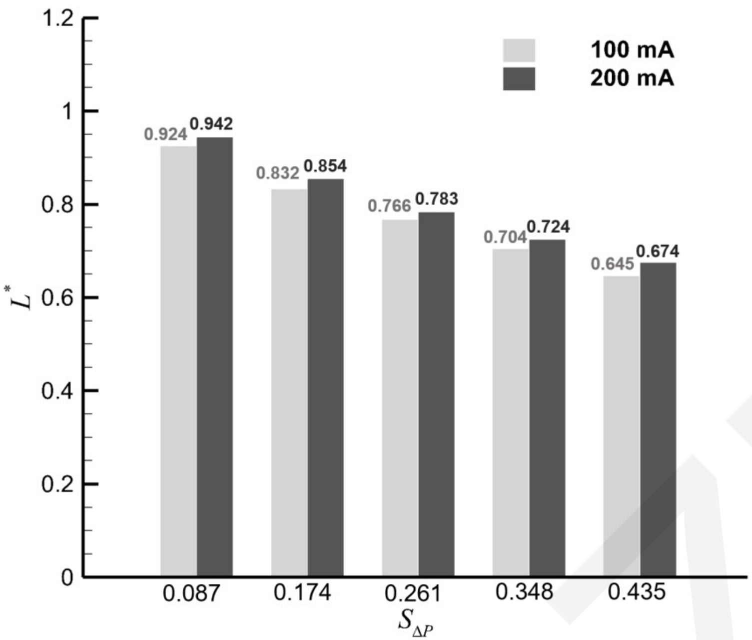

Fig. 9 Dimensionless separation lengths with MHD control at different electromagnetic inputs

■ MHD Control Mechanism

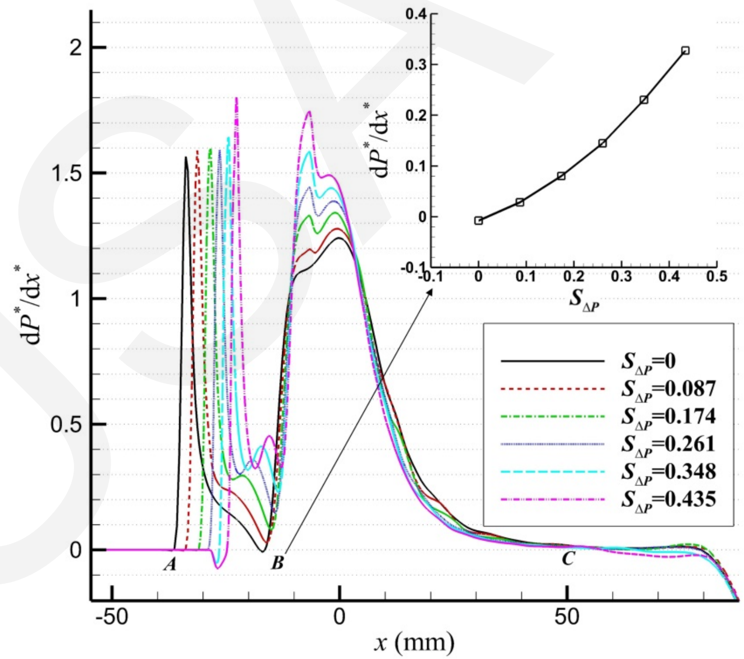

Fig. 10 Dimensionless pressure gradient distributions along the *x*-axis under different MHD parameters

- ➢ It can be seen that the dimensionless pressure gradient at point B after control is of the same order as the MHD parameter, and that these maintain an approximately linear relationship with each other. The new definition of MHD parameter adopted here equals the magnitude of the pressure uplift in the isobaric area to reach another force balance of STBLI organization.

Conclusions

- Regarding MHD control techniques employing MHD plasma actuators, the effectiveness of this control depends on the location of control where the mechanisms can be different. The closer to the wall of the D-type MHD control, which is located at the isobaric zone in the separation bubble, the better the reduction of the STBLI separation length.

- The pressure gradient of the isobaric zone in the separation bubble was approximately the same magnitude as the applied Lorentz force, and there was an approximately linear relationship between the pressure gradient and the Lorentz force after D-type MHD control.

- The newly proposed MHD interaction parameter is clearer in its physical meaning and can be further applied to predicting the MHD controllability of STBLI.

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