Active Control of a Planar Offset Attaching Jet Using Synthetic Jet Actuators

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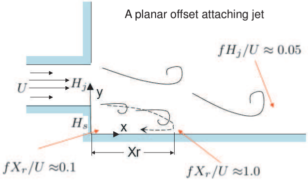
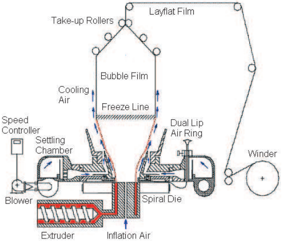
Background: cooling flow in blown-film manufacturing process



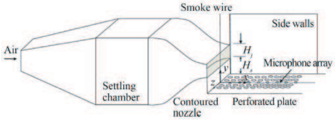
- Attaches to wall forming a re-circulation region, known as 'Coanda effect';
- Time-averaged reattachment length $X_r/H_s \approx 4$ to 6 (Gao & Ewing, 2007);
- Characteristic frequency: $fX_r/U \approx 0.1$ inside recirculation region; $fX_r/U \approx 1.0$ near $x = X_r$; $fH_j/U \approx 0.05$ away from exit.



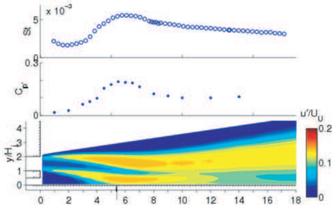
http://www.plasticstechnology.com

Cooling jets used in blown-film process

Control of an offset attaching jet



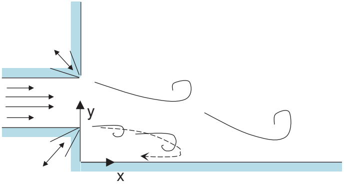
Perforated wall used by Gong *et al.*



Co-flowing wall jet used by Gao & Ewing

- Passive: Gong *et al.* (2014) used a perforated bottom wall, they found the low frequency flapping motion ($fX_r/U \approx 0.1$) was removed;
- Active: Gao & Ewing (2007,2008,2014,2015) examined a constant flow rate co-flowing wall jet, they found
  - fluctuations along the inner shear layer modified when low flow rate jet added,
  - wake type of structures emerged when large velocity co-flowing jet added; local heat transfer rate near the reattachment point enhanced.

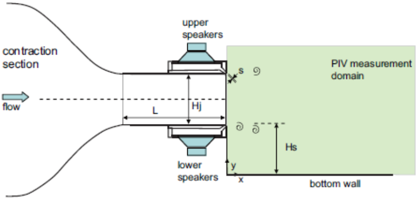
Objectives

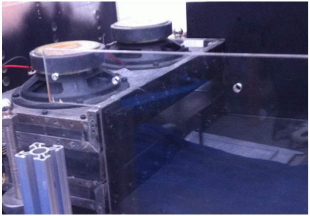


Offset jet forced using synthetic jet actuators

- To examine effect of synthetic jet on the development of a planar wall jet with an offset ratio of $H_s/H_j = 1.0$, including
  - time-averaged re-attachment location X_r;
  - time-averaged velocity U, Reynolds stresses $\overline{u^2}$, $\overline{v^2}$ and $\overline{uv}$;
  - flow structures.
- Test parameters:
  - synthetic jet at the upper and lower edge of the jet;
  - forcing frequencies $f^* = 0.08$ to 0.45, $f^* = fH_j/U_o$

Experiment facility

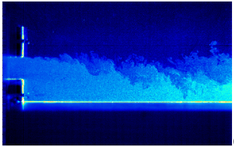




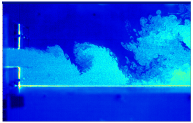
Schematics and a picture of the test rig

- Blow down jet facility, 0.75kW blower, settling chamber, contoured nozzle, 2D contraction 10:1;
- Jet height $H_j = 30mm$, aspect ratio (W/H_j) 10, offset ratio $H_s/H_j = 1.0$, mass flow averaged exit velocity $U_o = 8.0m/s$, Reynolds number 15300;
- Two zero-net-mass-flux actuators used, each has two 8cm diameter, 4Ω, 40W speakers, jet width $s = 1mm$, forcing strength u'/U_o=0.3, u' is root-mean-square of the jet velocity during the 'exhalation' portion of the cycle;
- A LaVision 2D PIV system was used to measure the velocity one the $z = 0$ plane, 100μs time interval, 2000 image pairs acquired at 25Hz.

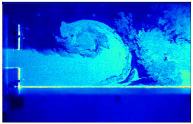
Laser-smoke visualization using PIV



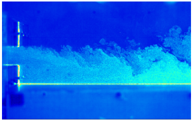
(a)No Control



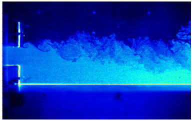
(b)$f^* = 0.08$ the **lower** actuator



(c)$f^* = 0.08$ the **upper** actuator

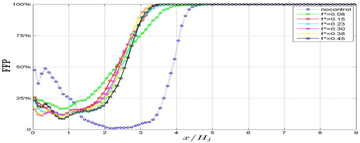


(d)$f^* = 0.45$ the **lower** actuator

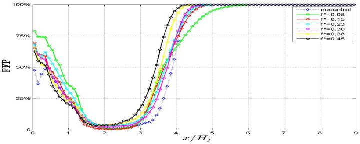


(e)$f^* = 0.45$ the **upper** actuator

Time-averaged reattachment location, X_r

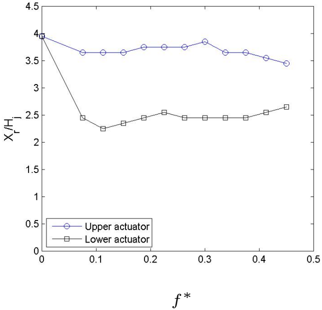


lower actuator



upper actuator

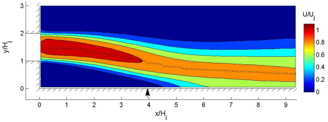
Distributions of the forward flow percentage (FFP) near wall ($y/H_j = 0.1$)



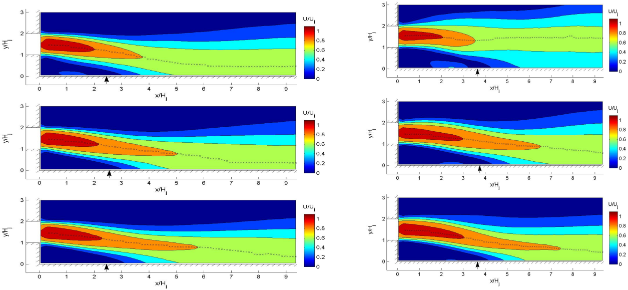
Time-averaged reattachment Location

Distributions of the time-averaged re-attachment location where forward flow ratio was 50% (Spazzini *et al.* 2001)

Effect of actuation on the mean flow



$f^* = 0.0, \ \sqrt{U^2 + V^2}/U_o$



$f^* = 0.08$

$f^* = 0.23$

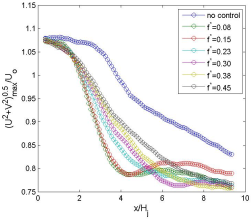
$f^* = 0.38$

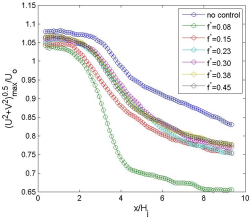
lower actuator

upper actuator

Maximum local velocity and jet half width

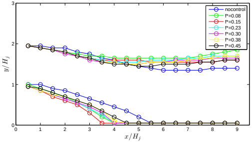
Max. local velocity

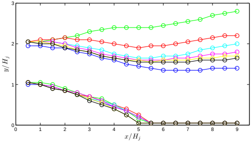




Jet half

width



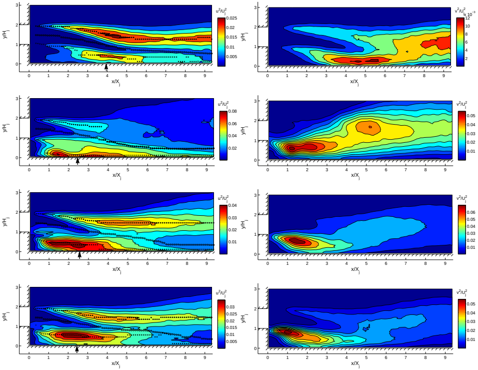


Lower actuator

Upper actuator

Effect of actuation on the shear layers

lower actuator



$f^* = 0.00$

$f^* = 0.08$

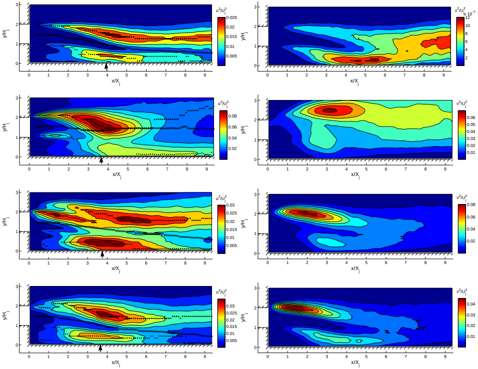
$f^* = 0.23$

$f^* = 0.38$

$\overline{u^2}$ $\overline{v^2}$

Effect of actuation on the shear layers

upper actuator



$f^* = 0.00$

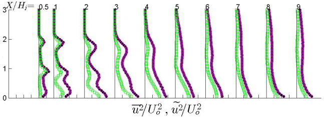
$f^* = 0.08$

$f^* = 0.23$

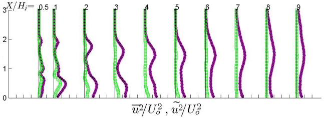
$f^* = 0.38$

$\overline{u^2}$ $\overline{v^2}$

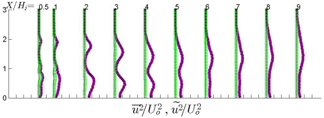
Phase-averaged and time-averaged Reynolds normal stresses $\overline{\widetilde{u}^2}$, $\overline{u^2}$, lower actuator



$f^* = 0.08$



$f^* = 0.23$



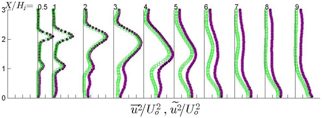
$f^* = 0.45$

- Velocity measurements were phase averaged, 2000 realizations were separated into 50 groups according to the phase of the actuation, phase angle within $\pm 3.6^o$ in each group, velocity for group k is

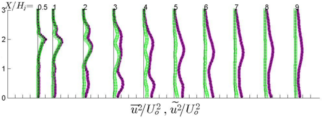
$$\widetilde{u}_k = \frac{1}{N}\sum_{j=1}^{N} u_{k,j}.$$

- when forced at $f^* = 0.08$, phase-averaged stress $\overline{\widetilde{u}^2}$ was similar to time-averaged stress $\overline{u^2}$;
- when forced at $f^* \geq 0.23$, contributions from $\overline{\widetilde{u}^2}$ to $\overline{u^2}$ were small, due to the changes in the shear layer frequencies.

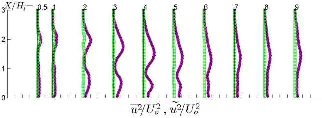
Phase-averaged and time-averaged Reynolds normal stresses $\overline{\widetilde{u}^2}$, $\overline{u^2}$, upper actuator



$f^* = 0.08$



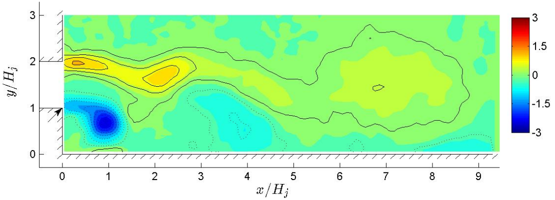
$f^* = 0.23$



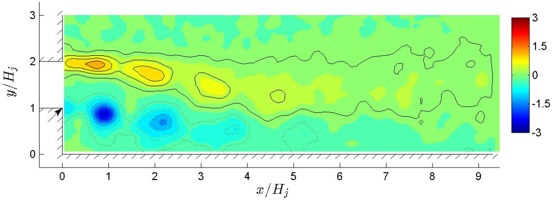
$f^* = 0.45$

- when forced at $f^* = 0.08$, phase-averaged stress $\overline{\widetilde{u}^2}$ similar to time-averaged stress $\overline{u^2}$, larger than forcing the inner shear layer;
- when forced at $f^* \geq 0.23$, contributions from $\overline{\widetilde{u}^2}$ to $\overline{u^2}$ were small.

Phase-averaged vorticity ($\widetilde{\omega}_z$), lower actuator

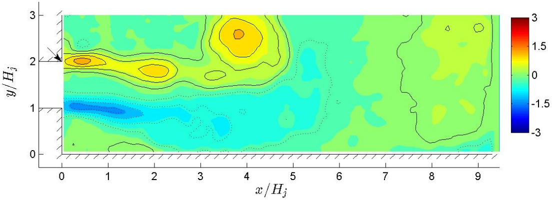


$$f^* = 0.08$$

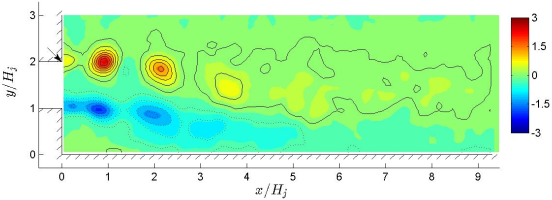


$$f^* = 0.45$$

Phase-averaged vorticity ($\widetilde{\omega}_z$), upper actuator



$f^* = 0.08$



$f^* = 0.45$

Conclusions and future work

Conclusions:

- Experiments were performed to investigate the affect of synthetic jets forcing location and frequency on the development of a planar offset attaching jet with $H_s/H_j = 1.0$ and $Re = 15\,300$;
- Low frequency forcing at $f^* = 0.08$ enhanced a flapping motion of the jet, especially when applied at the upper edge of the planar jet, spreading rate of the jet increased significantly;
- Time-averaged re-attachment length decreased when forced at all the frequencies examined, at either location.

Future work:

- Effect of the forcing amplitude u'/U_o =0.1, 0.2 and 0.4 will be examined;
- Combinations of the two synthetic jets will be examined, in-phased and anti-phased actuation;
- Effect of actuation on the convective heat transfer rate will be investigated.

Thank you!