Study of a Naturally Oscillating Triangular-Jet Flow

by

Soon-Kong Lee

THE UNIVERSITY OF ADELAIDE
School of Mechanical Engineering
South Australia, 5005, AUSTRALIA

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Contents

Abstract

This thesis reports on the structure of the flow inside a nozzle which produces a naturally oscillating jet flow. The nozzle consists of a short cylindrical chamber with a concentric triangular-inlet orifice at one end and a circular exit lip at the other end. This triangular-jet nozzle was developed from the "fluidic-precessing-jet" (FPJ) nozzle, which has a similar arrangement of components, but has a circular rather than a triangular inlet. For reliably oscillating flow, the FPJ nozzle should have an inlet-to-chamber expansion ratio of at least 5.0, a chamber length-to-diameter ratio between 2.6 and 2.8, and an exit-lip height of about 0.1 chamber diameters.

The triangular-jet nozzle produces a continuously and aperiodically oscillating jet flow which is different from the FPJ flow. The oscillation occurs at smaller inlet-to-chamber expansion ratios ($2.1 \lesssim D/d_{e1} \lesssim 3.5$) and over a wider range of chamber lengths ($2.0 \lesssim L/D \lesssim 2.5$). The initial spreading angle of the jet flow is smaller, but is still much larger than that of non-oscillating, axisymmetric turbulent-jet flows. In addition, the external "oscillating-triangular-jet" (OTJ) flow has preferred azimuthal directions which are aligned with the three corners of the orifice. The kinetic-energy-loss coefficient of the OTJ nozzle is much smaller than that of the FPJ nozzle because oscillation occurs at much smaller inlet-to-chamber expansion ratios.

For a narrow range of length-to-diameter ratios ($1.00 \lesssim L/D \lesssim 1.25$), the triangular-inlet nozzle can also produce a non-oscillating or "stationary deflected triangular jet" (SDTJ) which reattaches asymmetrically to the inside surface of the cylindrical chamber. The SDTJ has a weak tendency to oscillate, which suggests that flow patterns required for self-excited oscillation are already present in the SDTJ flow. Surface-flow visualisation and surface-pressure measurements in the SDTJ nozzle have provided the location of critical points and bifurcation lines on the chamber wall, and from this the topology of the SDTJ flow is deduced. Some details of the flow such as a jet-reattachment node near the chamber exit and a strong swirl adjacent to the inlet orifice are known from previous studies of the FPJ flow, but there are many newly observed features. The most easily identified of these are two sink-focus separation points, one on each side of the reattachment node but closer to the inlet plane. The foci counter rotate and are of unequal size. Reverse flow through the exit plane of the chamber is attracted to the larger focus.

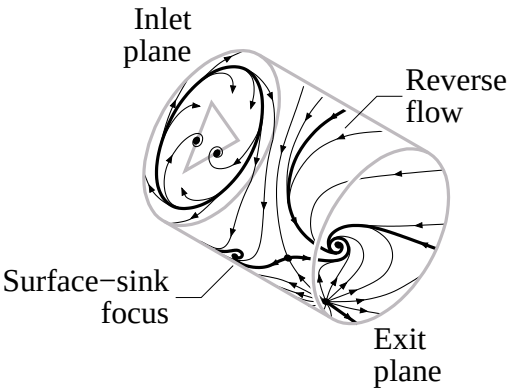
The vortex core rising from each focus is entrained by the reattaching-jet (SDTJ) flow and is drawn out of the chamber.

A backward-facing pressure probe placed in the OTJ “reattaching-flow” region of chamber wall can be used as a reliable detector of jet-flow oscillation. Cross-correlating the signal from this detector probe with simultaneous static-pressure measurements elsewhere on the chamber wall gives a conditionally-averaged pressure on the wall of the OTJ chamber. The OTJ wall-pressure distribution has the same features as the SDTJ surface-pressure distribution, but it has greater asymmetry about a mirror plane drawn through the chamber axis and the detector probe.

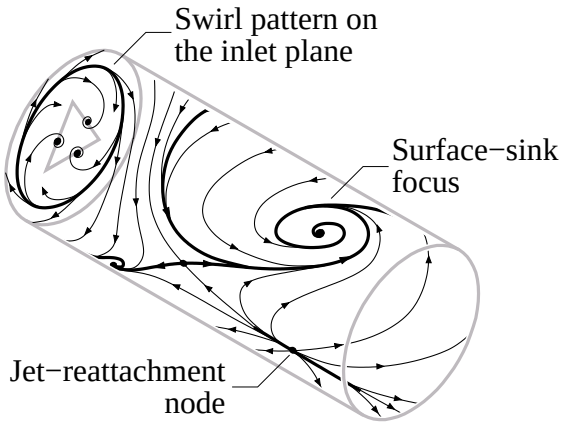
An array of three backward-facing pressure probes has been used as an “event detector” for conditionally-sampled (PIV) measurements of non-axial velocity components in cross-sections of the OTJ nozzle. The event-detection scheme responds only to a preselected (counter-clock-wise) direction of motion of the oscillating-jet flow. The streamline patterns constructed from the conditionally-sampled measurements confirm the presence of the jet-reattachment node, the swirl and the sink foci identified from the SDTJ surface-flow visualisation.

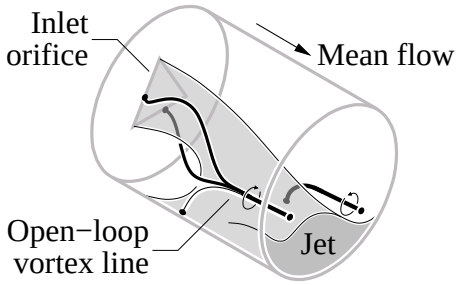
The shear-layer interaction between the jet from the triangular orifice and the swirl (adjacent to the inlet plane) produces strong longitudinal vortices in the ensemble-averaged flow. The jet flow distributes these vortices through the length of the chamber. Vortex cores representing the vortices are reconstructed by tracking streamline foci from one PIV cross-section plane to another. The tracking process includes the connection and termination of vortex cores in a manner which is consistent with the Helmholtz vortex law. In this flow field, the vortex core produced by the swirl and the vortex core rising from the larger sink-focus vortex on the chamber wall are connected to form a loop. The extent to which this vortex loop is contained within the chamber determines whether or not the flow is oscillating.

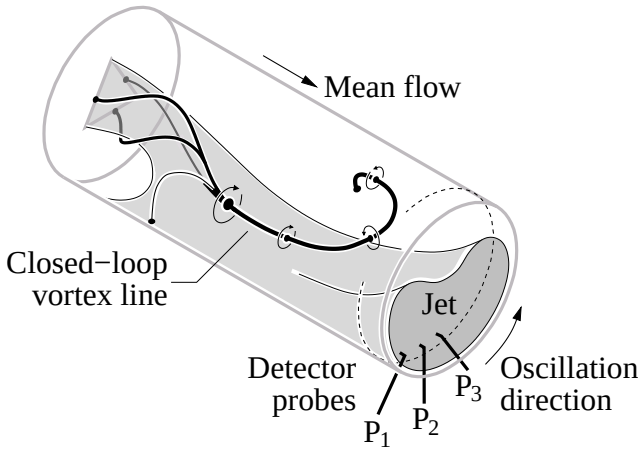
If only a small fraction (e.g. 8%) of the vortex circulation passes through the exit plane of the nozzle, the loop is trapped inside the chamber and the deflected jet oscillates. If the length of the chamber is halved, about 35% of vortex circulation escapes from the nozzle and the oscillation stops.



The stationary deflected triangular jet (SDTJ)







The oscillating triangular jet (OTJ)

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S. K. L.

Declaration

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S. K. L.
February, 2009

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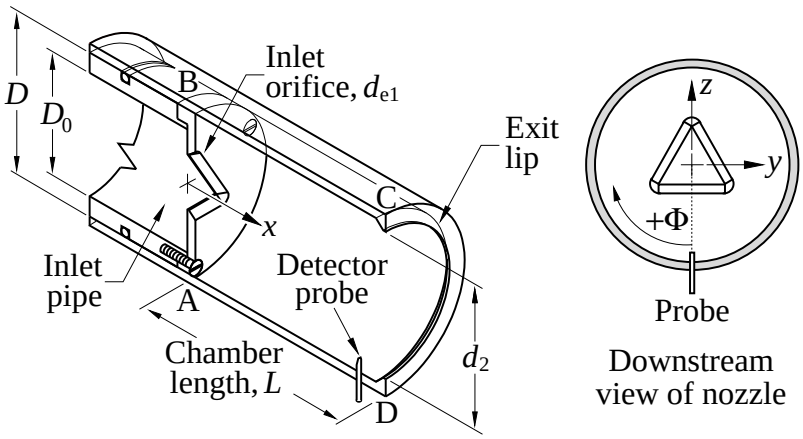
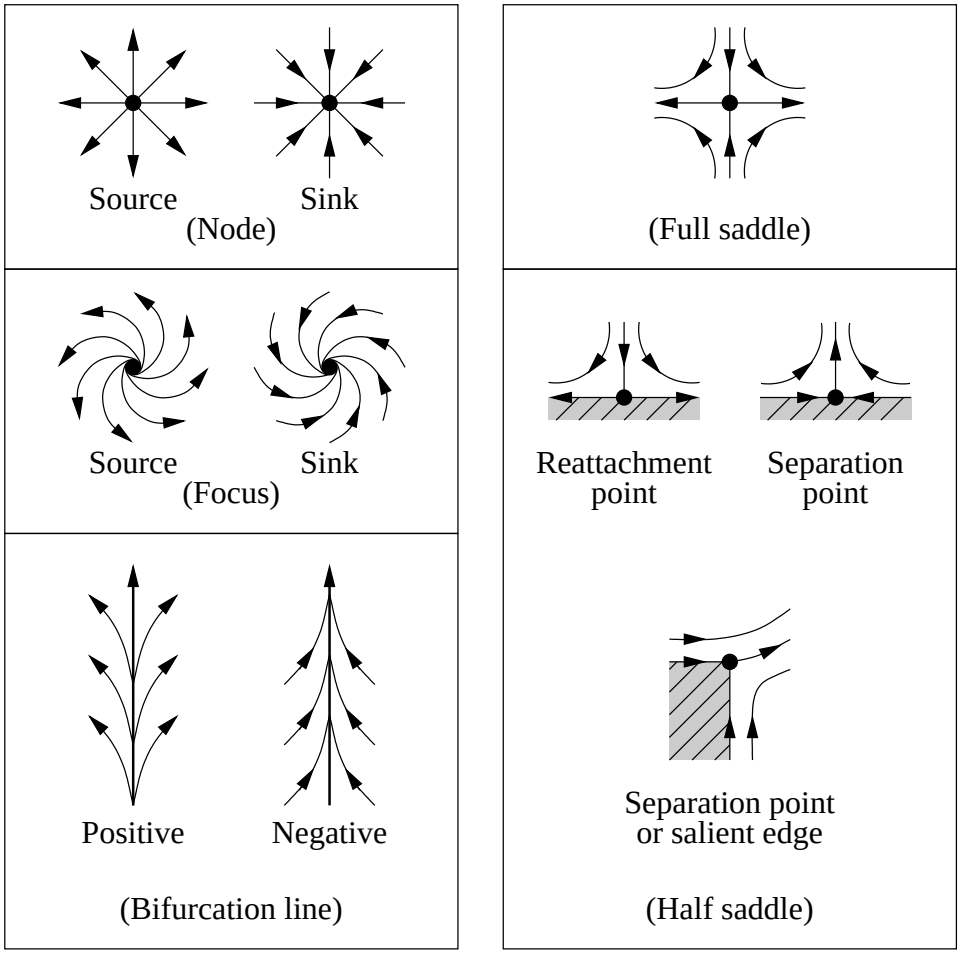


Nozzle components and geometric parameters.



Critical points and bifurcations.

Notation

Geometric parameters and coordinate system

D	chamber diameter
D_0	inlet-pipe diameter
d_1, d_{e1}	inlet-orifice (equivalent) diameter
d_2	exit-lip diameter
L	chamber length
x, y, z	streamwise, horizontal and vertical scales/directions

Jet-flow parameters

f_p	precession/oscillation frequency
P	pressure
P_0	inlet-pipe pressure
P_∞	ambient pressure
Q	supply flow rate through the nozzle
q_1	dynamic pressure of bulk flow through the inlet orifice, $q_1 = \frac{1}{2}\rho {U_1}^2$
t	time
U_0	bulk flow velocity in the inlet pipe, $U_0 = Q/\left(\frac{1}{4}\pi {D_0}^2\right)$
U_1	bulk flow velocity at the inlet orifice, $U_1 = Q/\left(\frac{1}{4}\pi {d_{e1}}^2\right)$
U_{cl}	nozzle-centreline flow speed

Coefficients and dimensionless groups

C_d	discharge coefficient of the inlet-orifice flow, $C_d = \sqrt{\frac{1}{K-1}\left[(D_0/d_{e1})^4 - 1\right]}$
C_p	pressure coefficient, $C_p = P/q_1$
K	loss coefficient of supply flow through the nozzle, $K-1 = (P_0 - P_\infty)/(\frac{1}{2}\rho {U_0}^2)$
Re_0	Reynolds number of the inlet-pipe flow, $Re_0 = D_0 U_0/\nu$
Re_1	Reynolds number of the inlet-orifice flow, $Re_1 = d_{e1} U_1/\nu$
St_1	Strouhal number of the inlet-orifice flow, $St_1 = f_p d_{e1}/U_1$

Flow-topology symbols

F	focus/vortex
N	node
NB	negative-bifurcation line
PB	positive-bifurcation line
S	saddle point

Greek Symbols

Λ	decay rate of jet-flow speed along the nozzle centreline
ν	kinematic viscosity of working fluid
ω	vorticity
Φ	azimuthal angle
π	circumference-to-diameter ratio of a circle
ρ	density of working fluid
Θ	jet-spreading angle

Other symbols

f (...)	a function of a parameter
$\langle \ldots \rangle$	ensemble average (or average of conditionally-sampled data)

Abbreviations

FPJ	fluidic precessing jet (as shown below)
OTJ	oscillating triangular jet
SDTJ	stationary deflected triangular jet

NOTE:
This figure is included on page xxii of the print copy of the thesis held in the University of Adelaide Library.

Air-bubble flow visualisation in the FPJ nozzle (from Nathan et al. [1998]).
Inlet orifice and exit lip are at ① and ②, respectively. Greyscales are inverted.