Nozzle R&D for a 20-m/s, 1-cm-diameter Mercury Jet

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Neutrino Factory and Muon Collider Collaboration Meeting

February 16, 2005

http://puhep1.princeton.edu/mumu/target/
The Best Nozzle is No Nozzle(?)

Reservoir at pressure $P$ with small aperture:

$$v_{\text{reservoir}} \approx 0, \quad v_{\text{jet}} \approx \sqrt{\frac{P}{\rho}}.$$  

Jet emerges perpendicular to the plane of the aperture.

Reservoir + short nozzle:

No reservoir, just a straight tube. $v_{\text{jet}} = v_{\text{tube}}$:

Most nozzle R&D is concerned with making a jet break up quickly and uniformly (atomizing), rather than with preserving the jet.

Kirk T. McDonald  
MUON COLLABORATION MEETING, BERKELEY, FEB. 16, 2005
Conservation of Energy vs. $F = dP/dt$ at a Contraction? (Borda, 1766)

Incompressible fluid $\Rightarrow V_1A_1 = V_2A_2$.

\[ A_2 \ll A_1 \Rightarrow V_1 \ll V_2. \]

Conservation of Energy $\Rightarrow$ Bernoulli’s Law:

\[ P_1 + \frac{1}{2} \rho V_1^2 = P_2 + \frac{1}{2} \rho V_2^2. \]

\[ V_1 \ll V_2 \Rightarrow V_2^2 \approx 2\frac{P_1 - P_2}{\rho}. \]

Argument does not depend on the area.

$F = dP/dt$:

Mass flux $= \rho V A$.

Momentum flux $= \rho V^2 A$.

Net momentum flux $= \rho (V_2^2 A_2 - V_1^2 A_1)$

\[ = \rho V_2 A_2 (V_2 - V_1) \approx \rho V_2^2 A_2. \]

Force $\approx (P_1 - P_2) A_2$.

\[ F = \frac{dP}{dt} \Rightarrow V_2^2 \approx \frac{P_1 - P_2}{\rho}. \]

Consistency $\Rightarrow$ dissipative loss of energy,

OR jet pulls away from the wall and contracts.

Kirk T. McDonald

Muon Collaboration Meeting, Berkeley, Feb. 16, 2005
Cavitation can be induced by a sharp-edged aperture.

A jet emerging from a small aperture in a reservoir contracts in area:

\[ A_{\text{jet}} = \frac{\pi}{\pi + 2} A_{\text{aperture}} = 0.62 A_{\text{aperture}} \]
\[ d_{\text{jet}} = 0.78 d_{\text{aperture}} \]

2-d potential flow (conservation of energy) \( \Rightarrow \) analytic form:

\[ x = \frac{2d}{\pi + 2} (\tanh^{-1} \cos \theta - \cos \theta), \quad y = d - \frac{2d}{\pi + 2} (1 + \sin \theta), \]

\[ \theta = \text{angle of streamline}, \quad -\frac{\pi}{2} < \theta < 0. \]

90\% of contraction occurs for \( x < 0.8d \).

Good agreement between theory and experiment.
Cavitation is highly likely because of the low pressure at the nozzle exit, and the high velocity in the nozzle.

\[ P_{\text{static}} = P_{\text{stagnation}} - \frac{1}{2} \rho V^2 \]

- \( \rho \) is density
- \( V \) is velocity
- If \( P_{\text{static}} < P_{\text{sat}} \), then mercury will cavitate

For 20 m/s, \( \frac{1}{2} \rho V^2 = 400 \text{ psi} \)

For 30 m/s, \( \frac{1}{2} \rho V^2 = 900 \text{ psi} \)

The CFD model is not conservative in predicting cavitation due to the transient aspect of the flow which is not simulated.

In the SNS Target Test Facility mitred bends, CFD results showed much less severe conditions than computed here.
\[ \mu = \frac{V}{\sqrt{2/\rho(P_1-P_2)}} \]
Mercury Jet Parameters

- Diameter \( d = 1 \text{ cm} \).
- Velocity \( v = 20 \text{ m/s} \).

The volume flow rate of mercury in the jet is

\[
\text{Flow Rate} = vA = 2000 \text{ cm/s} \cdot \frac{\pi}{4} d^2 = 1571 \text{ cm}^3/\text{s} = 1.57 \text{ l/s} = 0.412 \text{ gallon/s} = 94.2 \text{ l/min} = 24.7 \text{ gpm}. \tag{1}
\]

The power in the jet (associated with its kinetic energy) is

\[
\text{Power} = \frac{1}{2} \rho \cdot \text{Flow Rate} \cdot v^2 = \frac{13.6 \times 10^3}{2} \cdot 0.00157 \cdot (20)^2 = 4270 \text{ W} = 5.73 \text{ hp}. \tag{2}
\]

To produce the 20-m/s jet into air/vacuum out of a nozzle requires a pressure

\[
\text{Pressure} = \frac{1}{2} \rho v^2 = 27.2 \text{ atm} = 410 \text{ psi}, \tag{3}
\]

IF no dissipation of energy.

The mercury jet flow is turbulent: the viscosity is \( \mu_{\text{Hg}} = 1.5 \text{ cP} \), so the Reynolds number is

\[
\mathcal{R} = \frac{\rho d v}{\mu} = 1.8 \times 10^6. \tag{4}
\]
Dissipation and Cavitation Predicted by Fluid Dynamics Codes

(Mark Wendel, ORNL)

400 psi pressure drop predicted in vicinity of nozzle due to internal dissipation of energy.

Cavitation predicted at entrance to nozzle if hard edged.
At the center of the magnet, the centers of the mercury jet and the proton beam should coincide.

The nozzle should be about 45 cm upstream of the center of the magnet (whose bore is 15 cm).

Mercury jet comes up from below the proton beam at about 33 mrad (35 mrad in above table).

The top of the nozzle must be at least 5 mm from the proton beam (8 mm in above table).

Jacques Lettry:
After a search for mercury-compatible commercial pumps that could meet the above requirements, we purchased a 4000 Series, Model D-DH2(AA) centrifugal pump from R.S. Corcoran, powered by a 20-hp, 480 V motor from Baldor.
Nozzle Test Mercury Loop

Mercury loop with horizontal jet viewable for 30” in a lexan channel.

Lexan outer containment vessel sitting in a stainless-steel pan.

Mercury reservoir, 6” long, 5.5” diameter, with replacable nozzle plate.
Nozzle Plate

The aperture in the nozzle plate is tilted by 35 mrad with respect to the axis of the mercury reservoir.

Nozzle plates will be built with the aperture offset from the center, with a dummy proton beam pipe, and/or a short tube-type nozzle.