CAVITATING VENTURI OSCILLATION
Revision A

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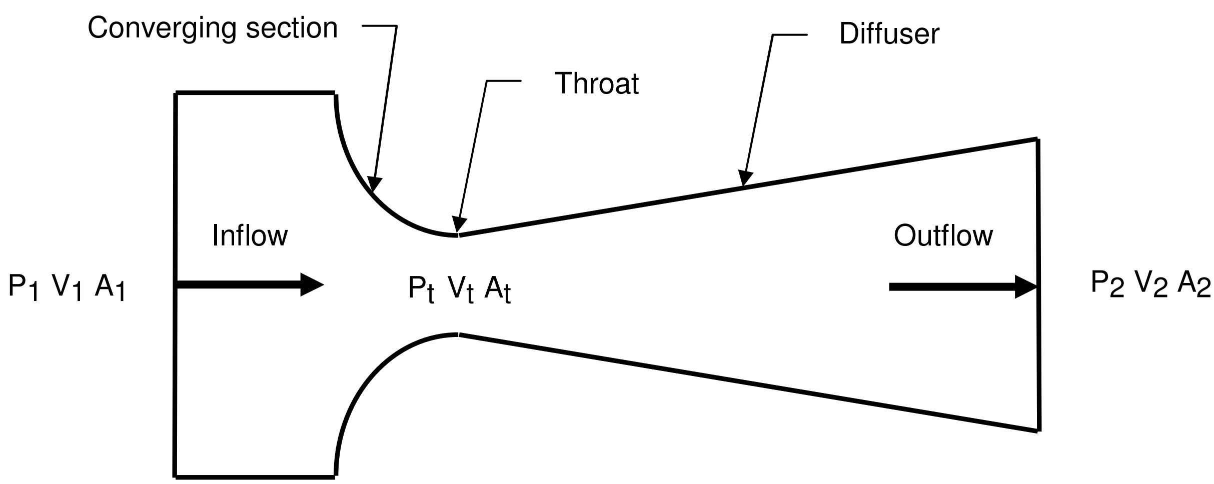

Figure 1. Schematic of a Cavitating Venturi

Note that $P_1 > P_t$

Introduction

The Venturi effect is the reduction in fluid pressure that results when a fluid flows through a constricted section of a nozzle.

A cavitating venturi is a nozzle operating with a throat pressure equal to the vapor pressure[1] of the fluid at the corresponding temperature. The nozzle is designed to keep the fluid flow rate fixed or locked. Thus, the flow rate is not dependent on the outflow conditions.

The nozzle throat is sized such that the differential pressure generated from the inlet section to the throat reduces the fluid's absolute pressure to its vapor pressure point so that it starts to

[1] The vapor pressure of the fluid is the equilibrium pressure of a vapor above the fluid. It is thus the pressure of the vapor resulting from evaporation of a fluid above a sample of the fluid in a closed container.

vaporize or boil, which is cavitation. This starts when the downstream pressure P_2 is less than 85-90% of the upstream pressure P_1.

The resulting vapor bubble begins to physically block the throat passageway, preventing any additional increase in flow rate.

If the inlet pressure is increased, then the throat pressure likewise increases, taking the liquid at the throat out of its vapor pressure point range. The cavitation bubbles collapse during this phase.

Additional flow may now pass through the nozzle throat which in-turn generates a higher differential pressure. This decreases the throat pressure to the vapor pressure point again and a new, higher fixed flow rate is established.

The cavitation vapor bubbles thus regulate the flow. The bubbles also provide a sort of isolation so that any fluctuations at the outlet, or downstream of the throat, do not affect the flow parameters at the inlet.

This effect is similar to gas flow in a nozzle where the flow is choked due to a shockwave.

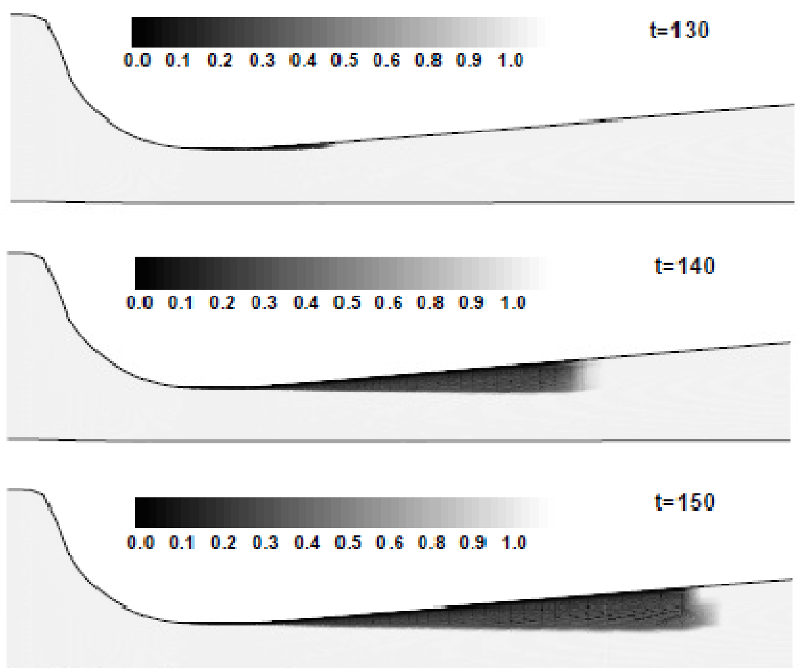

Figure 2. Vapor Cavity Formation, as shown by a Density Contours, Courtesy of Reference 1.

The vapor cavity is anchored to the nozzle throat.

Oscillation

The vapor cavity forms and collapses in a quasi-periodic manner. A half-cycle of this process is shown in Figure 2.

The researchers in Reference 1 performed a series of tests using different fluids and nozzle geometries. In one case for liquid hydrogen, they measured a sinusoidal oscillation at 400 Hz.

Furthermore, they determined that this oscillation can cause the mass flow rate to vary by 1 to 2%, despite the intention of the design.

The maximum flow rate corresponds to the time when the cavity is near its largest value; the growth of the cavity acts to push fluid that is already in the diffuser out the exit.

During the collapse phase the opposite effect is present as liquid fills in the volume previously occupied by the vapor cloud.

The cavity oscillation produces unwanted sound and vibration.

Rocket Engines

Cavitating venturis are used to control the propellant flow into a rocket combustion chamber.

The venturi provides a mechanism to keep flow rate constant during the ignition transient when the downstream pressure in the combustion chamber is rising rapidly.

Furthermore, the venturi nozzle may have a movable, tapered *pintle* valve to control the flow rate by varying the throat area.

Fastrac Engine

Figure 1. Fastrac Engine, Static Fire Test

The NASA Fastrac engine was a liquid engine which used RP-1 kerosene and liquid oxygen as propellants. The propellants were fed in the combustion chamber via a single shaft, dual impeller turbopump. The engine was designed to produce 60,000 lbf thrust. The engine was built and tested, but was never flown.

Bullard in Reference 1 described a test of the engine at the Marshall Space Flight Center (MSFC) TS116 Test Stand. He noted that sustained, large amplitude oscillations were observed near 530 Hz in the pressure data. These oscillations were detected in both the RP-1 feedline, downstream of the cavitating venturi, and in the combustion chamber. The driver of the instability was believed to be feedline excitation driven by either periodic cavity collapse at the exit of the cavitating venturi or combustion instability. Further analysis showed that there was a feedline natural frequency at 530 Hz, which was excited into resonance by one of the candidate sources.

Bullard wrote that further testing and analysis of the resonance was planned. But whether this additional work was ever performed and documented is unclear.

References

1. Changhai Xu, Stephen D. Heister, Steven H. Collicott, Che-ping Yeh; Modeling Cavitating Venturi Flows, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 7-10 July 2002.

2. B. Bullard, Transient Simulation of Pressure Oscillations in the Fuel Feedline of the Fastrac Engine Thrust Chamber, Sverdrup Technology, Inc, MSFC Group, 1998.

APPENDIX A

Variables

A_1	Inlet area
A_t	Throat area
P_1	Throat pressure
P_v	Vapor pressure
V_1	Inlet velocity
V_t	Throat velocity
ρ	Fluid density
$\dot{m}$	Mass flow rate
S_t	Strouhal number
L_D	Diffuser length
f	Frequency
Q	Volumetric flow rate

Formulas

The flow velocity at the throat is derived from the Bernoulli and continuity equations.

$$\frac{1}{2}\rho V_1{}^2 + P_1 = \frac{1}{2}\rho V_t{}^2 + P_v \tag{1}$$

$$\rho V_1 A_1 = \rho V_t A_t \tag{2}$$

$$V_t = \sqrt{\frac{2(P_1 - P_v)}{\rho} \frac{1}{1-(A_t/A_1)^2}} \tag{3}$$

The theoretical Bernoulli mass flow rate is

$$\dot{m} = \rho A_t V_t \tag{4}$$

Also note that

$$\dot{m} = \rho Q \tag{5}$$

The Strouhal number is defined as

$$St = \frac{f L_D}{V_t} \tag{6}$$