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HYDRAULIC AXISYMMETRIC FOCUSED-JET DIVERTERS WITH PNEUMATIC CONTROL

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ABSTRACT

In the fluidic technology hydraulic amplifiers are badly needed in the large flow [0.05 to 5 m^3/s (800 to 80,000 GPM)] and moderate pressure [30 to 200 N/cm^2 (45 to 300 psi)] class. The axisymmetric focused-jet amplifier is particularly suited for this application and has had considerable development for pneumatic digital control applications.

One development goal was to switch a liquid stream ON and OFF in very short time periods and without devastating water-hammer. A second goal was to eliminate moving or deflecting mechanical parts. A third goal was to provide a fluidic interface between a pneumatic logic circuit [2 to 10 N/cm^2 (3 to 15 psi) air pressure] and the hydraulic power amplifier. Supply pressures up to 27 N/cm^2 (40 psi) and supply flows up to 0.010 m^3/s (160 GPM) have been employed in the test of a model diverter. Pressure recoveries and power efficiencies of the order of 50 percent have been achieved.

A standing cavitation bubble is formed within the control cavity of the amplifier; thus it is possible to switch the flow with a pneumatic input without mechanical interface.

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HYDRAULIC AXISYMMETRIC FOCUSED-JET DIVERTERS WITH PNEUMATIC CONTROL

SUMMARY

Hydraulic amplifiers are needed in the large flows [0.05 to 5 m^3/s (800 to 80,000 GPM)] and moderate pressure [30 to 200 N/cm^2 (45 to 300 psi)] class. The axisymmetric focused-jet amplifier appears particularly suited for this application. A model has been built and tested at supply pressures up to 27 N/cm^2 (40 psi) and supply flows up to 0.01 m^3/s (160 GPM). Pressure recoveries and power efficiencies of the order of 50 percent have been achieved. Pneumatic control without mechanical interface has been developed, exploiting a standing cavitation bubble within the control cavity.

INTRODUCTION

Much interest has been shown in fluidic control applications for space flight. Of current interest from the long range reliability viewpoint is the replacement of conventional hydraulic servovalves by a fluidic vortex bridge and the replacement of control moment gyros by "fluid flywheels." Also of interest is the replacement of mechanical switches by fluidic circuits and the fast control of large liquid streams from ground to vehicle and within the vehicle without devastating "water-hammer."

Hydraulic amplifiers in the large flow [0.05 to 5 m^3/s (800 to 80,000 GPM)] and moderate pressure [30 to 200 N/cm^2 (45 to 300 psi)] class are badly needed for both fluid flywheels and liquid stream control. The axisymmetric focused-jet amplifier appears particularly suited for this application. The pneumatic version of this amplifier is well known in the fluidic literature and has been described both in popular survey articles [1,2] and in technical books [3,4].

A general discussion, comparing the basic features of axisymmetric and planar amplifiers, is given by Fox and Goldschmied [5]. This paper also gives the first description of the focused-jet axisymmetric monostable amplifier invented and developed by Goldschmied.

The basic aerodynamic principles of operation, the assembly design and stainless steel fabrication, and the pneumatic digital logic applications are described in Reference 6. Furthermore, dynamic testing methods for the amplifier in the NOR function have been proposed by Goldschmied [7] and presented together with preliminary experimental results.

All of this effort was directed to low-pressure [2 to 10 N/cm^2 (3 to 15 psi)] pneumatic operation for digital NOR logic application with objectives of minimum size and weight, minimum fluid power requirements, and maximum switching speed.

The major part of this development program was funded by NASA's George C. Marshall Space Flight Center* and is reported in Reference 8.

Shown in Figure 1 is a stainless steel array of 36 NOR gates of 0.0127 cm (.005 in.) jet width for a pneumatic digital control application from Reference 6. A single axisymmetric fluid NOR gate (of the same basic size as shown in Figure 1) as currently offered on the market is shown in Figure 2.

Switching times of 0.5 and 0.25 ms have been documented [6] at 3.5 N/cm^2 (5 psi) pneumatic supply pressure; a comparable Corning Glass Works planar NOR gate (Cat. No. FD 2-4-3730) has a switching time of 2 ms.

More recently it has become apparent that large hydraulic diverters would comprise an important application class for the axisymmetric focused-jet amplifier because of the expected rapid switching of large liquid flows without concomitant "water-hammer" pressure surges of devastating intensity.

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*Contracts NAS 8-11236 and NAS 8-20102

HYDRAULIC DIVERTER DEVELOPMENT

Preliminary Tests

The development of the hydraulic amplifier was started from the geometry given in Reference 8 and reproduced in Figure 3. The size was increased arbitrarily fivefold to 9.50 cm (3.74 in.) power-jet annulus diameter and to 0.127 cm (0.05 in.) power-jet width. This new size is exactly ten times that of the pneumatic NOR gates shown in Figures 1 and 2; also the new Reynolds number will be approximately one hundred times greater, thus affording a good opportunity to explore performance similarity between air and water and between small and large amplifiers.

A preliminary Plexiglas model was built and tested by Karimi [9] at low supply pressures [less than 30 N/cm^2 (40 psi)]. It was observed that even at low pressures a standing cavitation bubble was formed within the control-body cavity (Fig. 3) because of the suction exercised by the high-speed power jet. The vacuum recorded within the control cavity was of the order of 5 N/cm^2 (7.5 psi) below atmospheric pressure.

Any liquid input to the control cavity through the control pipe was observed to flash into vapor without effecting a "clean" switching of the power jet. It was soon found, however, that a pneumatic pressure input of some 10 N/cm^2 (15 psi) was quite effective in causing a "clean" and fast switching action by "exploding" the vapor bubble.

Thus a means was found to achieve a fluidic (no mechanical moving parts) interface between pneumatic logic and hydraulic actuation — all without the unacceptable effects of water-hammer.

Another observation made during these preliminary tests was that a substantial transitory thrust was obtained along the amplifier axis at the ON or OFF switching time. This thrust was estimated to be over one order of magnitude greater than the steady-state thrust caused by the mass-flow injection from the diverter's output port. This effect may be of great significance for the control of hydrospace vehicles (submarines etc.).

Note that the hydraulic diverter is monostable, similar to the pneumatic NOR amplifiers developed previously.

Advanced Diverter Development

Following the preliminary phase, a design study was made to produce an advanced version of the hydraulic diverter which would be of minimum size and weight and which would be capable of withstanding 200 N/cm^2 (300 psi) hydraulic supply pressure. Hard-anodized aluminum was to be used throughout with few exceptions where stainless steel was employed.

The cross section of the final design is presented in Figure 4. The maximum diameter is 15 cm (6 in.) and the length is 28 cm (11 in.). Six major parts may be identified in the cross sectional layout and can be fabricated on conventional machine tools by state-of-the-art technology. Displayed in Figure 5 are the diverter assembly (upper) and the exploded view of the device (lower).

Finally shown in Figure 6 is the comparison between the present hydraulic diverter and the well-known Corning Glass Works planar NOR gate.

Experimental Investigation

The experimental test layout of the hydraulic diverter is shown in Figure 7. The device was held submerged horizontally in an open-surface, constant-head flume and was supplied through a Venturi flowmeter by a separate pipe. The output load was provided by a set of removable nozzles, thus allowing the determination of the output flow Q_o once the output pressure P_o was measured.

The pneumatic control pressure P_c was measured, ranging from a substantial vacuum in the ON condition to an atmospheric vacuum in the OFF condition.

First the steady-state performance of the hydraulic diverter was investigated to determine output flow and output pressure as functions of the load for constant supply pressure. This is presented in Figure 8 as P_o (N/cm^2) against Q_o [m^3/s] for two supply pressures, P_s = 24 N/cm^2 (35 psi) and P_s = 27 N/cm^2 (40 psi). The dotted lines are isoefficiency curves for η = 30, 40, and 45 percent.

It is clearly seen that there are two distinct flow regimes for the hydraulic diverter, one regime from blocked load (zero flow) to about 0.008 m^3/s (125 GPM) and the other from 0.008 m^3/s (125 GPM) to wide-open load (zero pressure).

The supply flow has been found to be entirely independent of the load, from blocked to wide-open. There are no pressure surges upstream during switching at any load.

The static efficiency $\eta = \frac{P_o Q_o}{P_s Q_s}$ (neglecting the velocity pressure in the pipe since inlet and outlet diameters are equal) is plotted against output flow Q_o in Figure 9. Note that the efficiency is not affected by the supply pressure in the flow regime from blocked load to 0.008 m^3/s (125 GPM) but it is affected toward wide-open load. Indeed at 0.0145 m^3/s (231 GPM) the efficiency is zero for 24 N/cm^2 (35 psi) supply pressure and 25 percent for 27 N/cm^2 (40 psi).

Since the output flow Q_o can be as much as 0.0165 m^3/s (272 GPM) compared with a constant supply flow Q_s of 0.010 m^3/s (160 GPM), it is clear that the diverter causes strong entrainment effects and thus acts as a hydraulic jet pump with the additional feature of the fluidic ON/OFF control. As a jet pump, the present peak efficiency of 45 percent is unusually high. Conventional jet pumps peak mostly at 20 to 25 percent efficiency.

ANALYSIS

The analysis of the experimental results is concerned here primarily with the understanding of the low flow regime or "throttled-flow regime," of the high flow regime or "through-flow regime," and of the control-cavity suction with concomitant cavitation bubble.

The throttled-flow regime and the control-cavity suction are both based on the fluid phenomenon of curved jets. Such jets have been long exploited in engineering in many applications such as ground-effect vehicles, dynamic liquid seals, Coanda-effect propulsors, etc. Briefly a curved jet is capable of maintaining a pressure differential across itself because of its curvature and velocity The ideal pressure-differential maintained by a thick inviscid curved jet is plotted in Figure 10 for convenient reference. Now the pressure coefficients for the output pressure and for the control suction are both plotted in Figure 11. It is seen that the output coefficient Cp_o is essentially constant in the throttled-flow regime indicating correspondingly constant jet curvature ratio $\frac{T}{R} = 0.25$ and that the control suction coefficient Cp_c is constant throughout the entire flow range indicating a constant jet curvature ratio $\frac{T}{R} = 0.10$ regardless of load.

Shown in Figure 12 is a sketch of the flow pattern in the throttled-flow regime. The stagnation points are indicated for the attachment (Coanda) bubble and for the output curvature area. As long as there is an appreciable return flow, the jet curvature will be maintained constant and thus the output pressure will be kept up to its value. At some reduced load the decreased return flow will be insufficient to maintain its curvature and the jet will be "swallowed" into the output duct in an abrupt manner quite analogous to the "stall" of a ground-effect vehicle when the annular jet "focuses" itself and the lift is halved.

APPLICATIONS

There are innumerable applications of the hydraulic diverter with pneumatic input wherever there is a need to control a liquid stream in the minimum possible time without water-hammer surges and without mechanical moving parts to wear or jam. Some of the more significant utilization classes are as follows.

NASA and DOD Applications

Cryogenic fueling of space vehicles from the ground.

Propellant utilization thrust control of space vehicle through liquid fuel control.

Space vehicle attitude control without mass ejection or high-speed rotating masses with a "fluid flywheel."

Hydrospace flight and hovering control with and without mass ejection.

The "fluid flywheel" method of attitude control has been demonstrated by means of a small fluidic device. This device is an artificial heart pump built at the University of Utah and described by Goldschmied, Prakouras, and Nelson [10].

Figure 13 shows a 125 cm (50 in.) diameter loop of 1.9 cm (0.75 in.) diameter Tygon tubing connected with the centrally-located heart pump. The entire assembly and the supporting turntable [160 kg (350 lbm) total mass] were mounted on a high-grade rotating air-bearing support operating at 60 N/cm^2 (85 psi) air pressure. Thus, a very high ratio of inertia to friction was achieved, simulating to a good extent the rotating motion of a vehicle in free space.

The heart pump produces fairly sharp flow pulses against time as shown idealized in Figure 14. Correspondingly there will be a torque pulse (position or negative) for the flow rise or decay. The positive torque pulse starts the vehicle in angular motion. After a time increment the negative torque pulse stops the vehicle. No net energy has been gained but a net angular displacement has been achieved after a complete cycle.

Operating the heart pump at about 25 N/cm^2 (35 psi) air pressure results in a displacement of about 2 degrees per flow pulse.

The same effect can be achieved on a far larger scale using a conventional steady-state centrifugal pump and the hydraulic diverter to cut the flow ON or OFF as desired. The fluid flywheel appears attractive for long space missions because of its inherent reliability and conservation of mass.

Industrial Applications

Some typical applications are:

Metering of liquids in chemical and petrochemical process control

Pipeline control without water-hammer

Hydraulic mining with pulsating jets

Controllable jet pumping of slurries etc.

Automotive manifold fuel injection.

A typical industrial tank installation of the diverter is shown in Figure 15. The unit is submerged in the tank and is supplied by a motor pump with a tank-bottom inlet and a minimum output pressure of 25 N/cm^2 (35 psi). The pneumatic control is either closed for full hydraulic output flow or open for zero output flow. The pneumatic pressure required is of the order of 10 to 20 N/cm^2 (15 to 30 psi). If the tank liquid level is allowed to fall sufficiently to uncover the diverter's return ports, then the flow will be automatically switched OFF until the liquid level has risen again. This feature can be of great value in some applications where a minimum level must be maintained.

Comparison with Conventional Valves

Any discussion of applications of the hydraulic diverter would not be complete without reference to the presently available conventional hardware.

The only up-to-date compendium of fluid valve components is given by the Aerospace Fluid Component Designer's Handbook (USAF RPL-TDR-64-25), Volume I, in the following sections:

Section 5. 2 Shut-off Valves

Section 5. 3 Control Valves

Section 5. 5 Relief Valves

Section 5. 7 Explosive Valves

Section 6. 2 Valving Units

The types of valves capable of handling large flows with the fastest control action are the following:

Butterfly valve

Gate and blade valves

Flexible tube valve

Rotary slide and linear slide valves

All these valves are at least one order of magnitude slower than the diverter and all will cause water-hammer up the line. It can be concluded that there is no available hardware which can compete with the hydraulic diverter in its unique characteristics. On the other hand, it must be noted that its power efficiency is as yet only 45 percent; i. e. , it requires much more pumping power to use it on the line. In some systems the power is paramount while in others it can be neglected. No general rules can be stated.

CONCLUSIONS

From the evidence presented in this paper it may be fairly conclusive that the hydraulic axisymmetric focused-jet diverter has already reached a useful technological level for a great many industrial applications.

Further improvements in power efficiency up to 75 percent and switching speed are needed for most aerospace systems, as well as the utmost design refinement for minimization of weight and size.

While the present diverter design is monostable in keeping with the pneumatic NOR amplifier, a bistable diverter would also be quite useful and should become the goal of the next development phase.

Also an experimental effort should be made to investigate the upper pressure limit, if any, and to determine the best efficiency areas in terms of jet velocity and Reynolds number.

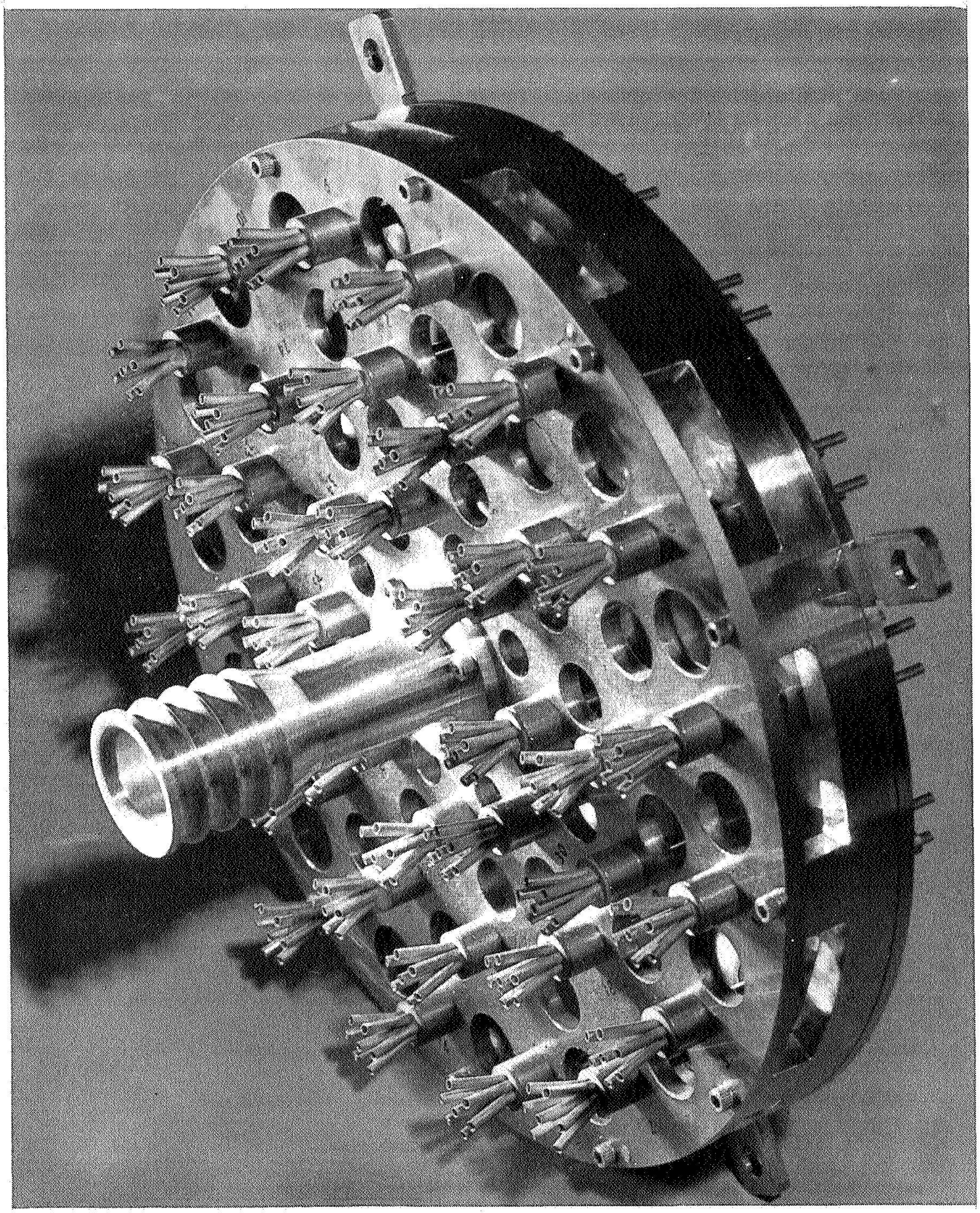

FIGURE 1. STAINLESS STEEL ASSEMBLY OF 36 PNEUMATIC AXISYMMETRIC NOR GATES FOR DIGITAL CONTROL

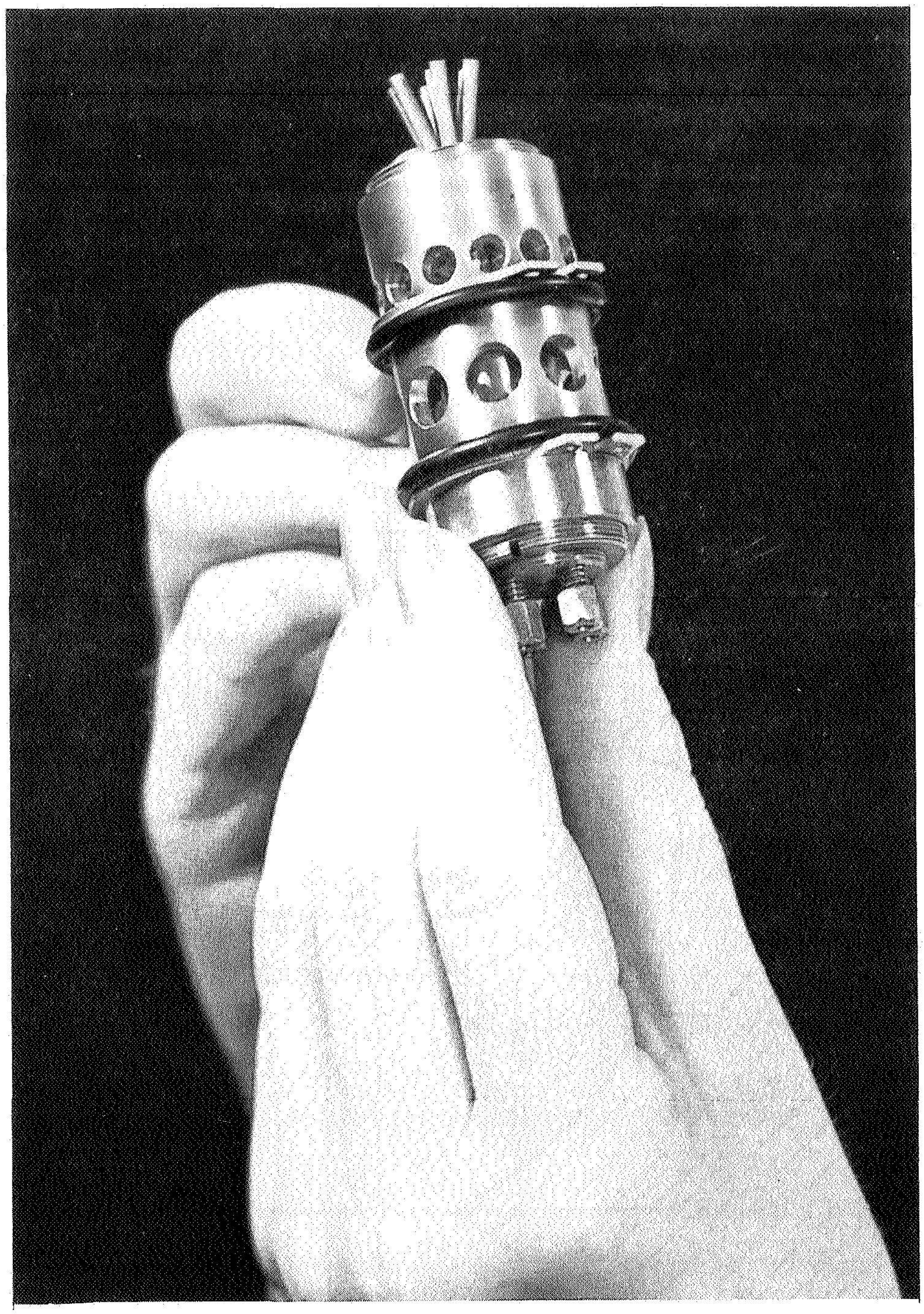

FIGURE 2. SINGLE STAINLESS STEEL PNEUMATIC AXISYMMETRIC NOR GATE

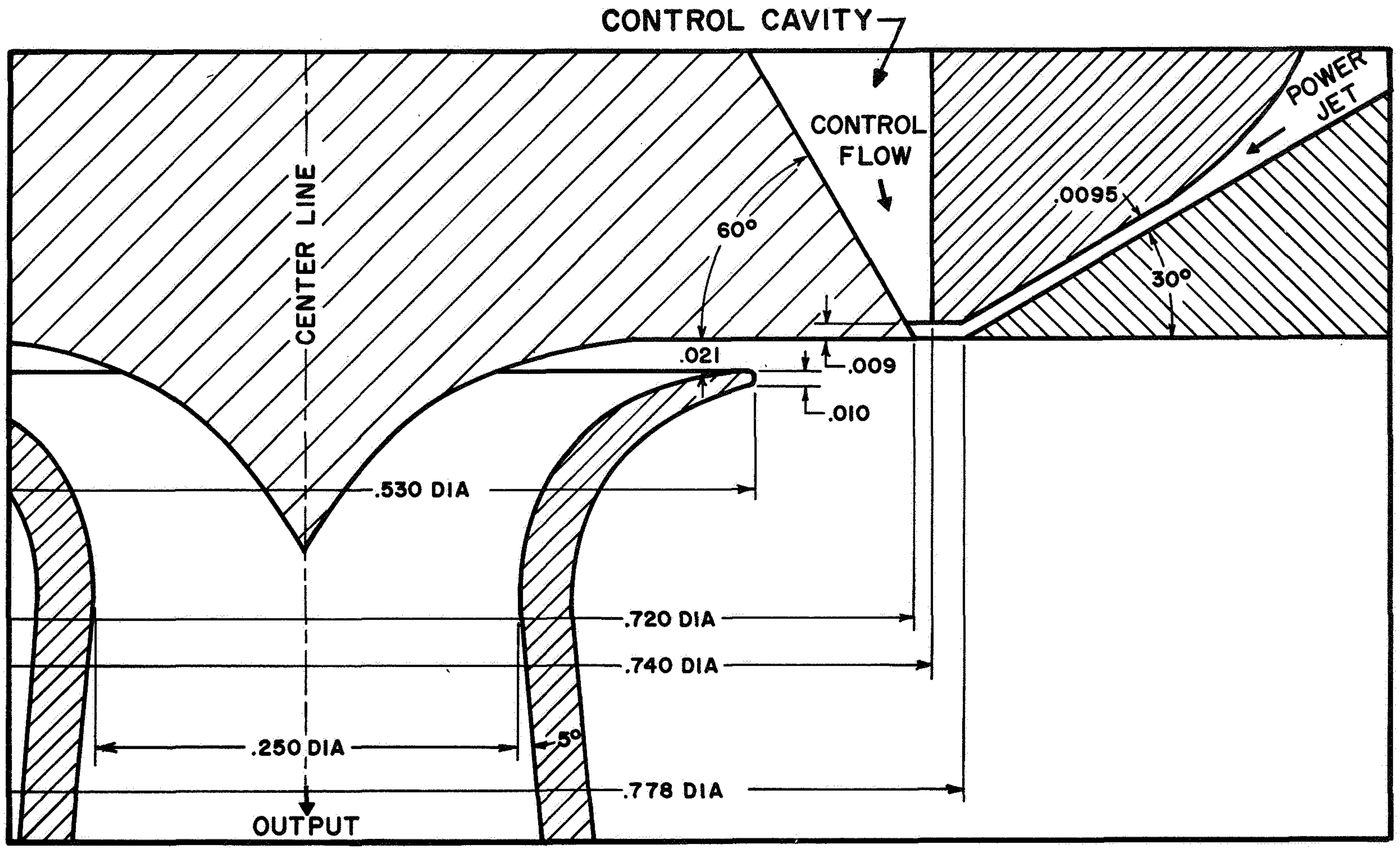

FIGURE 3. AXISYMMETRIC FOCUSED-JET INVERSE FLUID AMPLIFIER DETAIL OF INTERACTION REGION

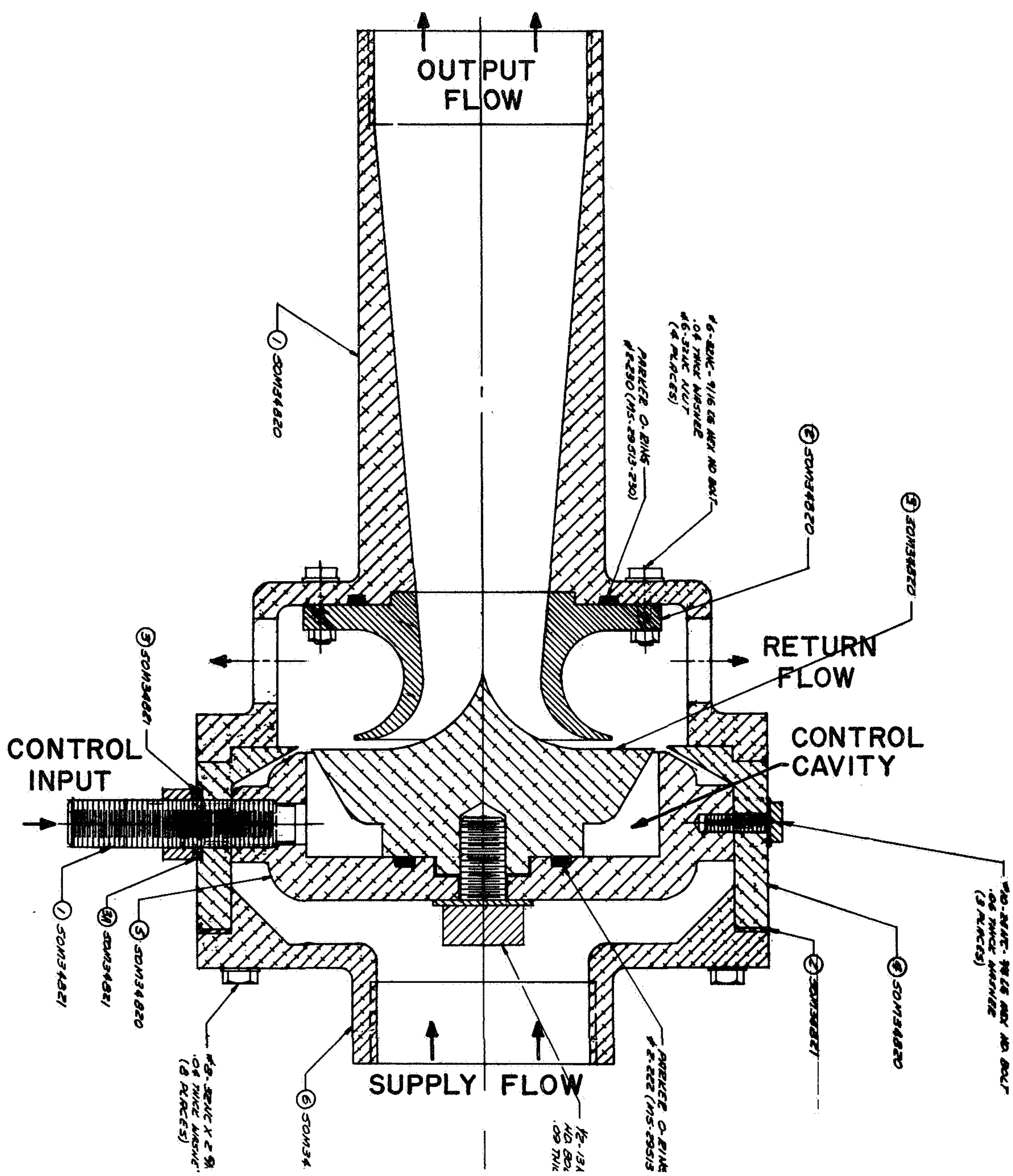

FIGURE 4. CROSS SECTION OF HYDRAULIC AXISYMMETRIC FOCUSED-JET DIVERTER

FIGURE 5. HYDRAULIC AXISYMMETRIC DIVERTER ASSEMBLY (UPPER), EXPLODED VIEW (LOWER)

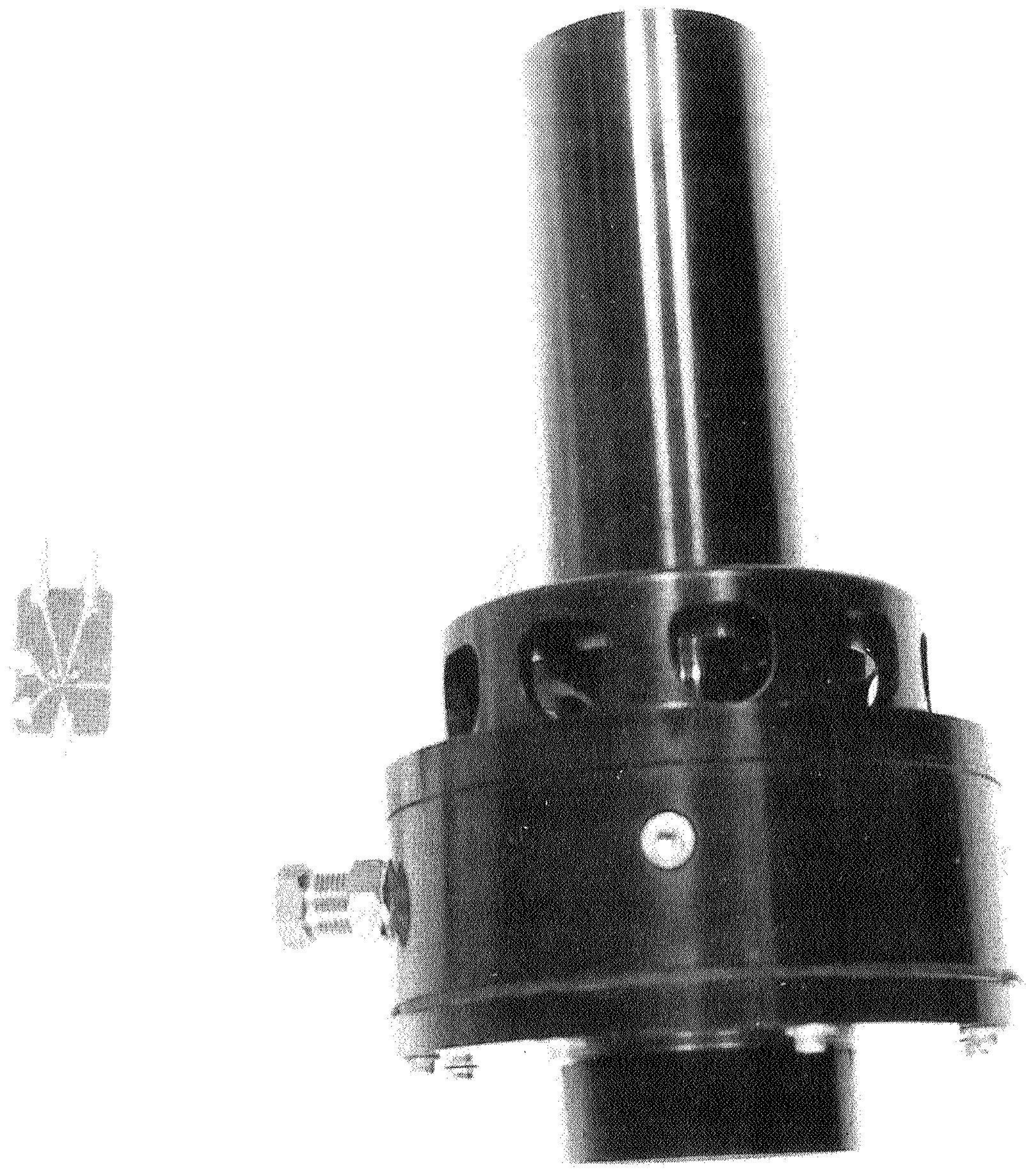

FIGURE 6. CORNING GLASS WORKS NOR GATE (LEFT) AND HYDRAULIC DIVERTER (RIGHT)

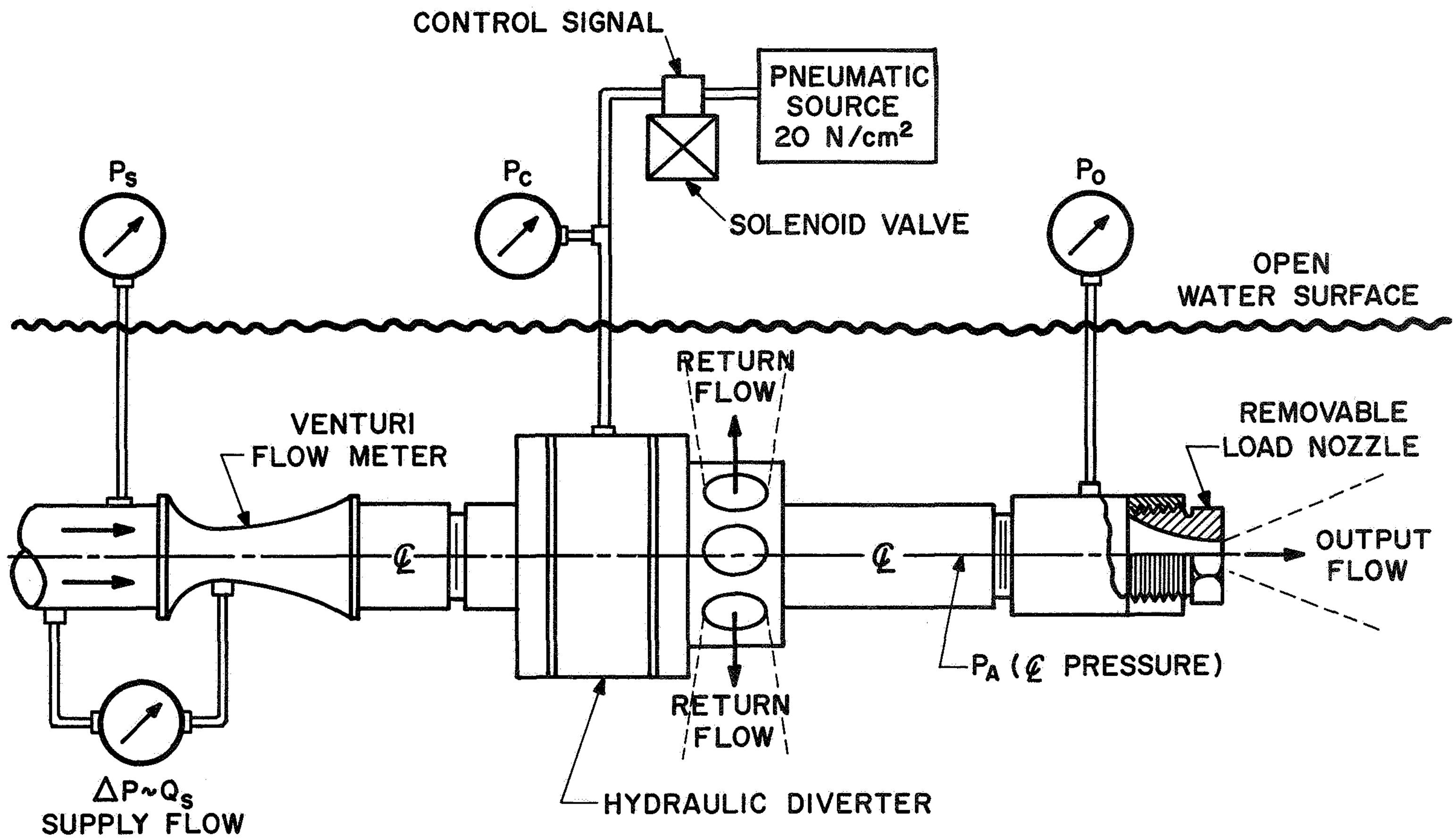

FIGURE 7. EXPERIMENTAL TEST LAYOUT OF HYDRAULIC DIVERTER IN OPEN CHANNEL

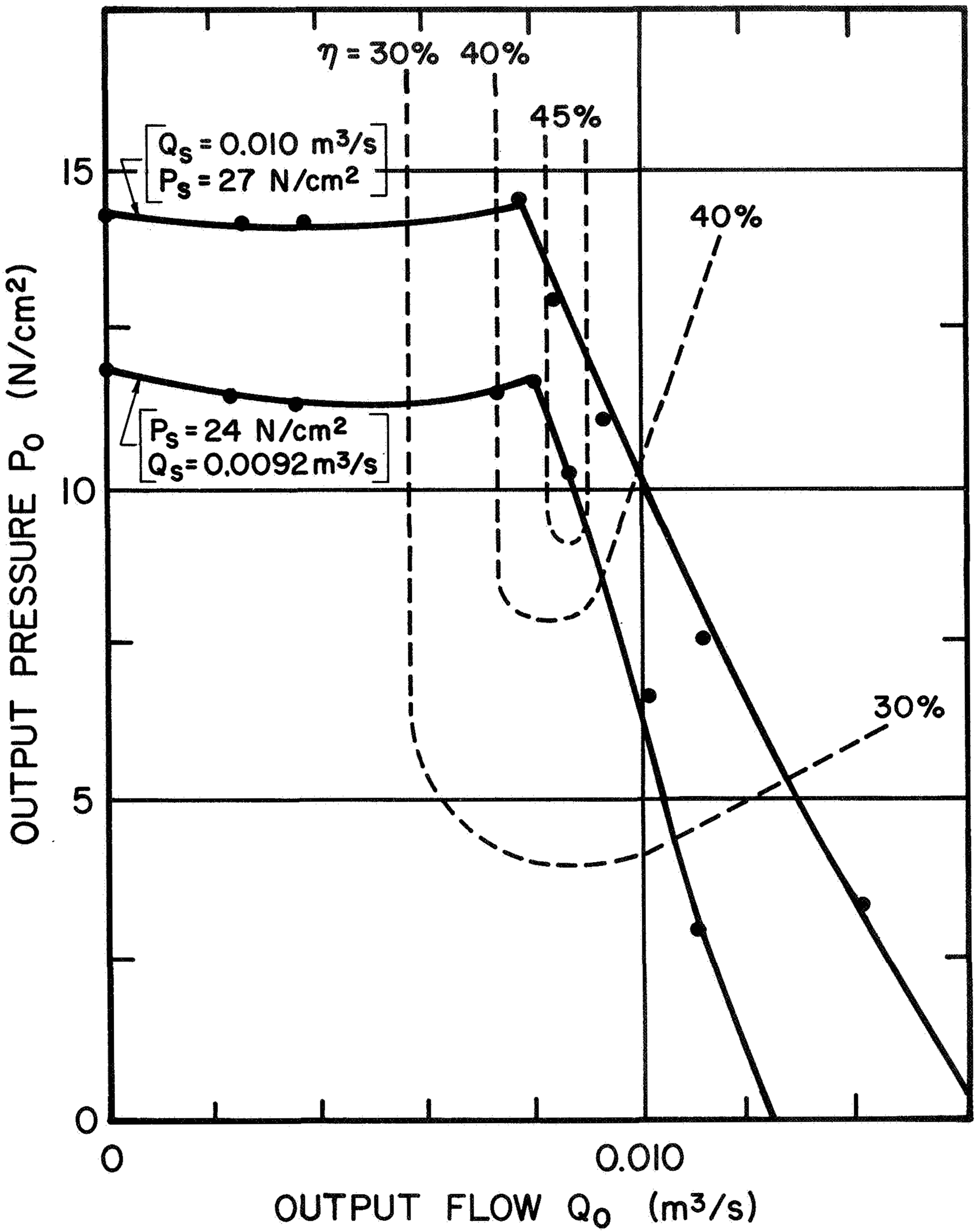

FIGURE 8. OUTPUT PERFORMANCE OF HYDRAULIC DIVERTER

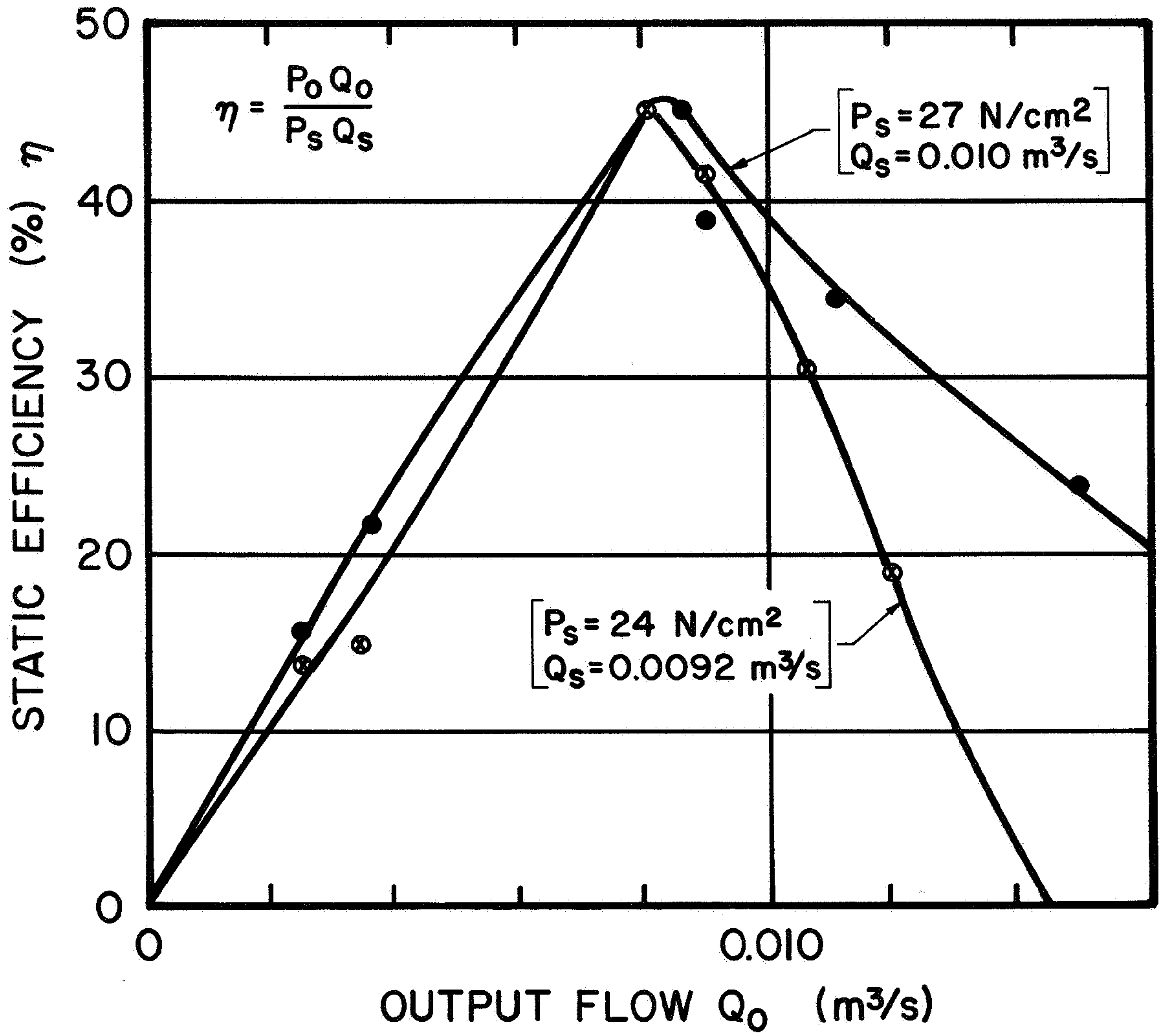

FIGURE 9. EFFICIENCY OF HYDRAULIC DIVERTER

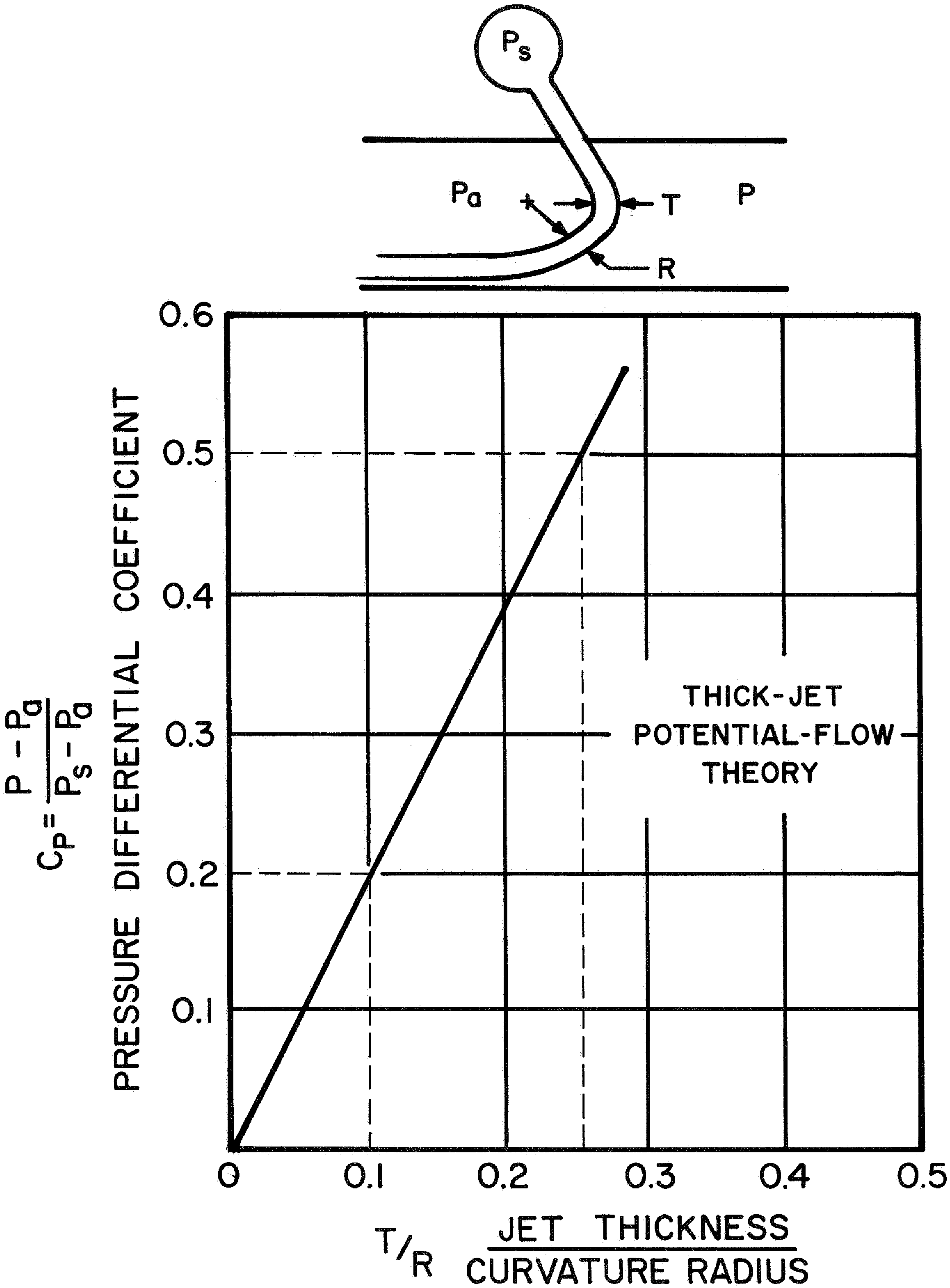

FIGURE 10. PRESSURE DIFFERENTIAL OF THICK INVISCID CURVED JETS

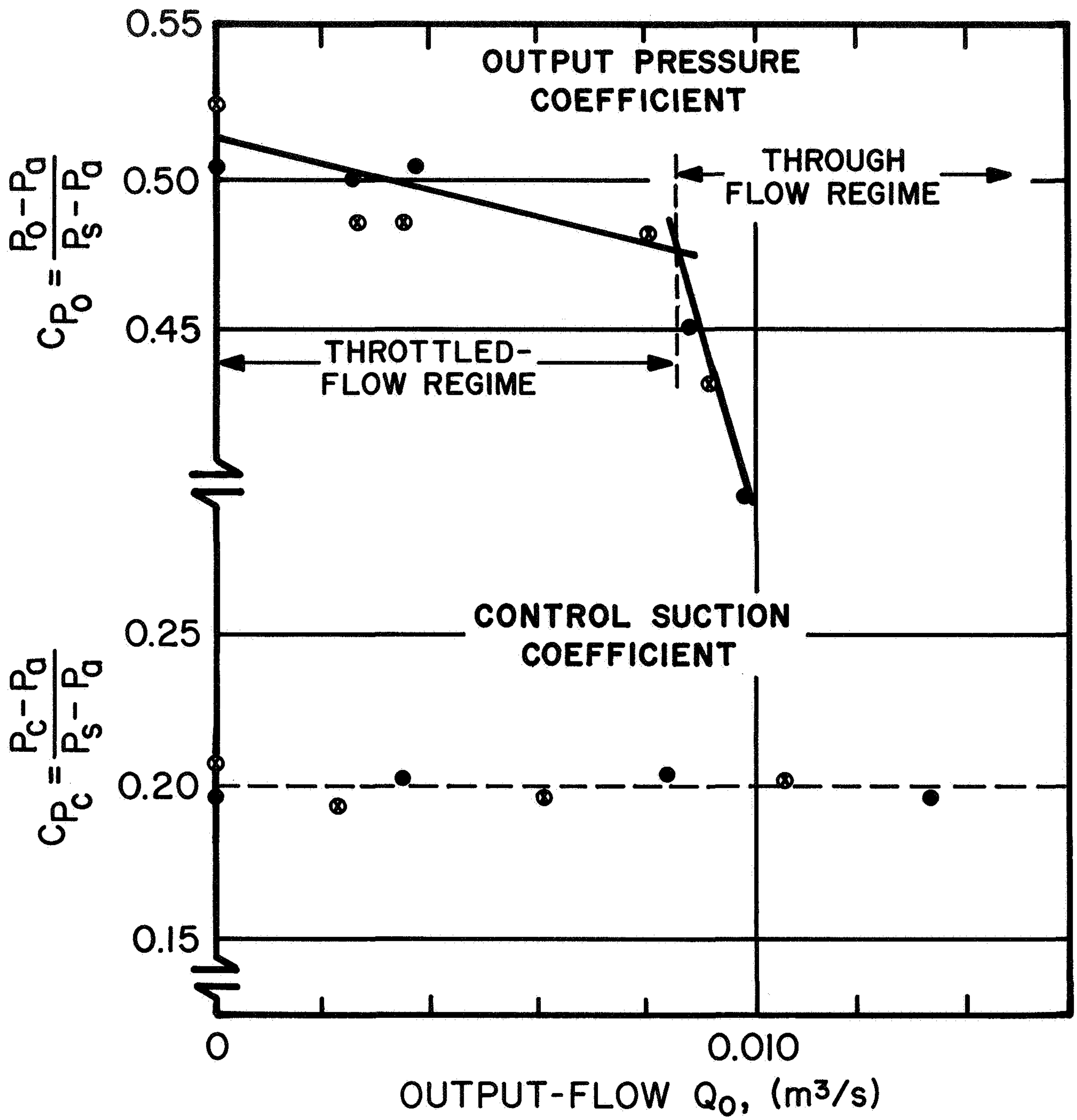

FIGURE 11. OUTPUT AND CONTROL PRESSURE COEFFICIENTS

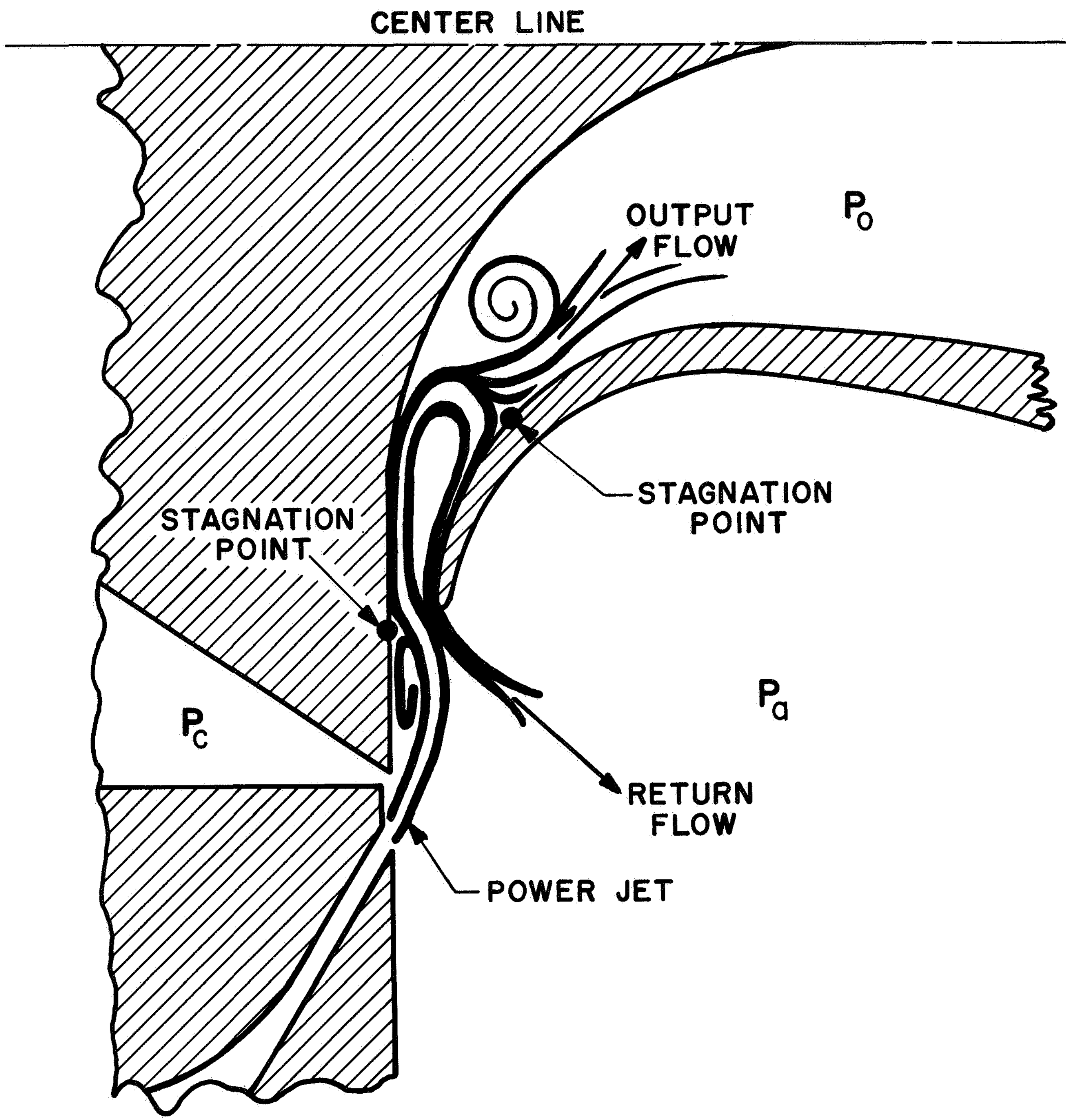

FIGURE 12. SKETCH OF FLOW CURVATURES IN THROTTLED-FLOW REGIME

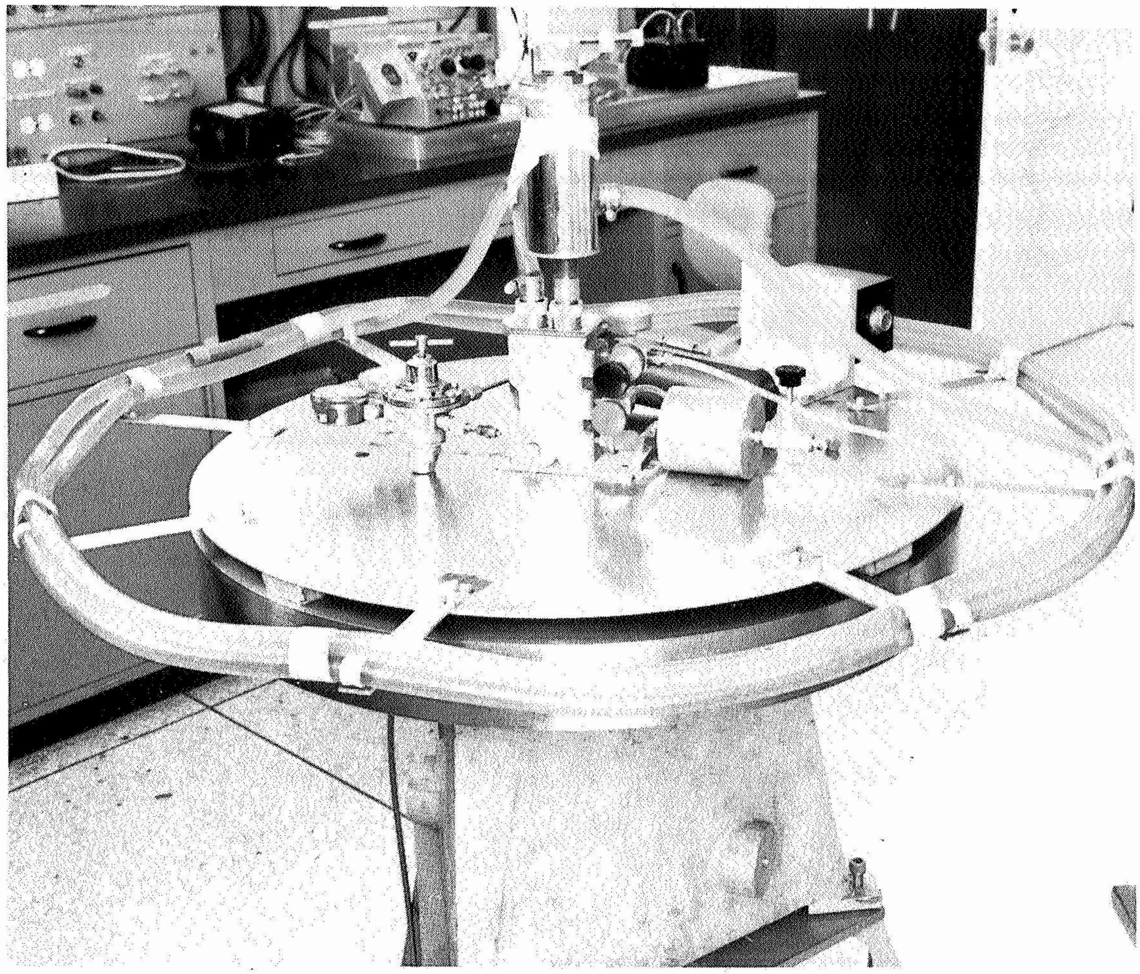

FIGURE 13. FLUID FLYWHEEL ATTITUDE CONTROL DEMONSTRATION APPARATUS

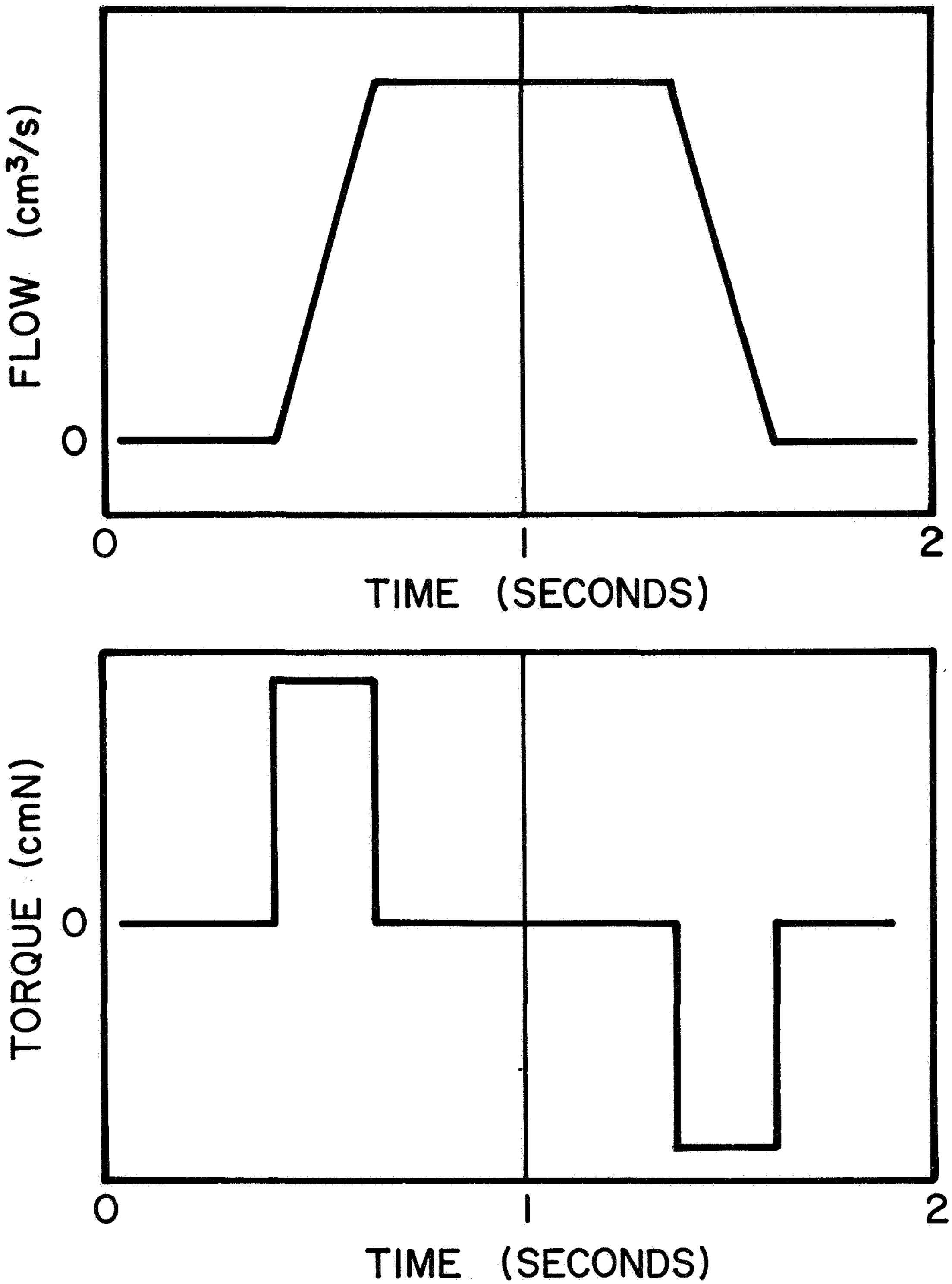

FIGURE 14. IDEAL FLOW AND TORQUE OF FLUID FLYWHEEL

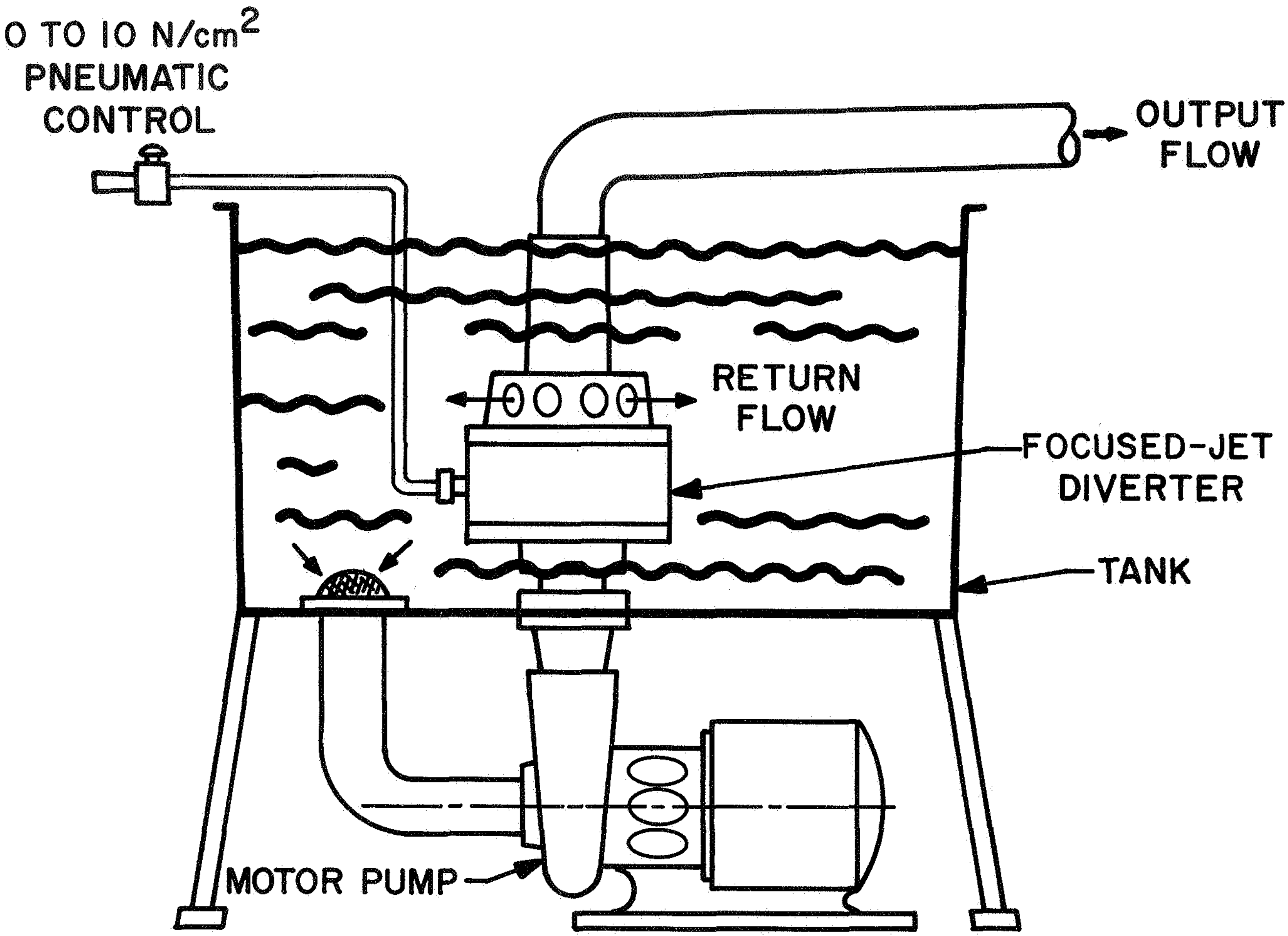

FIGURE 15. TYPICAL TANK INSTALLATION OF HYDRAULIC DIVERTER WITH PNEUMATIC CONTROL

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This report has also been reviewed and approved for technical accuracy.

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