AD722316

Technical Note N-1150

A FLUIDIC SYSTEM FOR MIXING TWO FLUIDS - DEVELOPMENT STUDY

By

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February 1971

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A FLUIDIC SYSTEM FOR MIXING TWO FLUIDS - DEVELOPMENT STUDY

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ZF 38.512.001.005

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ABSTRACT

Results of a study on the use of proportional fluid amplifiers for the mixing of two fluids are presented. The system proposed is considered capable of mixing fluids in varying mixture ratios. For this application, the fluidic device promises to be superior to conventional mechanical flow modulating devices. The fluidic mixing system being tested uses a double leg elbow amplifier and is designed for mixing hot and cold water.

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INTRODUCTION

Continuous mixing or blending of several fluids in desired proprotions is usually encountered in chemical, pharmaceutical, biomedical, water distillation, food, and sewage treatment industries. The immediate areas of Naval applications involving mixing of fluids range from shore-based facilities to deep sea operations. For instance, hot and cold fluids are mixed to regulate the temperature as required in diver heating systems. Mixing of helium and oxygen is carried out for breathing chambers in the deep sea diving operations. Fresh and recirculated air are mixed together in air-conditioning applications.

The problem of mixing two fluids invariably involves precise and repeatable metering of each fluid separately in accordance with the changes in ratio and total quantity of the mixture. One system of mixing hot and cold water in the desired ratio uses a thermostatically controlled three-way mixing valve.[1] The mixing process is accomplished by a sliding disc which by thermal action gradually covers the cold water inlet port as it uncovers the hot water inlet port thereby rendering a hotter mixture. The reverse motion of the disc yields a colder mixture. It should be mentioned here that the device delivers a constant supply of water through the outlet port at varying ratios of the two mixing fluids. The device to date has been used on domestic heating controls. Other systems for modulating the flow of fluids, and hence applicable to mixing operations, utilize pumps with variable output flow rates. Also flow-control valves are used as a means of flow modulation. These valves are usually controlled automatically either by electrical or mechanical means. These systems, since they have mechanical moving parts, are subject to relatively high initial and maintenance costs. Furthermore, the flow-control valves can develop problems like excessive internal leakage which produces poor flow modulating characteristics. Of more importance, the mechanical systems can have poor performance under extreme environments such as those of extremely high or low temperatures, corrosive fluids like seawater, or in applications subject to severe shock and vibration. A very promising method of improving the conventional mixing systems is by using the fluidic flow modulating devices.

In 1970 the Harry Diamond Laboratories identified a new technology called "fluidic devices." These devices contain no mechanical moving parts and possess the unique capability to perform sensing, logic, amplification and control functions simply by utilizing fluid dynamic phenomena. Considerable experimentation and development work in fluidic devices has been reported in the literature.[2] In practice these devices can function with all kinds of fluids.

Fluidic devices can be grouped into two basic categories: active or passive elements. Active elements commonly known as fluid amplifiers perform logic, amplification or control functions. There are two types of active fluidic elements: the digital amplifier and the proportional amplifier which, since they produce gain, require a separate power source. Passive elements, on the other hand, do not produce gain and do not require a separate power source. Typical passive fluidic devices are orifices, accumulators, fluid diodes, and small diameter long tubes.

Proportional fluid amplifiers such as the beam deflector, vortex, and fluid throttle types possess flow modulating characteristics. For example, a beam deflector fluid amplifier has been used in the "fluidic carburetor" reported in Reference 3. This carburetor uses the fluid amplifier to meter the flow of gasoline into the venturi thus eliminating the need for a float operated needle valve.

A study conducted at the Naval Civil Engineering Laboratory (NCEL) showed that the mixing of two or more fluids in desired proportions is feasible using proportional fluid amplifiers.[2] Mixing systems using suitably designed fluidic elements should have an insignificant amount of corrosion in the seawater environments and good performance under high temperature operations. Such systems have the potential for reducing costs and improving reliability for a variety of Naval applications.

This report describes the status of development of a fluidic system capable of handling 0-5 gpm of each of two fluids. In the development of the mixing system it was found necessary to design and test a proportional amplifier with a 0-5 gpm range since this component is not available commercially. The results of the testing on this amplifier are presented below. Two mixing system concepts for future tests are also presented.

CONCEPTUAL MIXING SYSTEM

A preliminary concept of a system designed for future tests for mixing of two fluids which is capable of maintaining a constant mixture ratio at varying flow rates is shown in Figure 1. A proportional fluid amplifier modulates the flow of one fluid and a mechanical valve controls the flow of another fluid as shown. With Fluid A as the control fluid and no control fluid flowing, Fluid B would be pumped through Passage R for return to its supply tank. As the control valve D is opened, it diverts a proportional amount of Fluid B through O for mixing with Fluid A at the junction point M. As Valve G is opened, increasing the flow of Fluid A, the venturi at V develops a lower pressure and diverts more fluid through O to M to maintain the mixture ratio constant. The proportion of Fluid B in the mixture can be changed by regulating Valve D. Since the system uses mechanical valves for controlling the flow of Fluid A, the concept is for non-corrosive fluids.

A proposed concept of a fluidic system for future tests designed for corrosive fluids such as seawater or some chemicals is shown in Figure 2. The system uses two proportional fluid amplifiers, one for each fluid. Fluids A and B are supplied to the mixing junction M by the fluid amplifiers S_1 and S_2, and through fluid lines O_1 and O_2 respectively. The fluid amplifiers control the flow of the two fluids to mix them in the desired ratios. The amplifiers are controlled by the signals tapped off from the venturi orifice on the mixture line MZ. For changing the mixture ratio the variable resistors V_1 and V_2 are provided on the control lines of the fluid amplifiers S_1 and S_2 respectively. These variable resistors are fluidic passive devices consisting of a resistance path of variable length which is varied with a control knob. The resistance of these devices is linear and they can be fabricated from non-corrosive materials. In systems which operate at a given fixed mixture ratio, fixed resistors can be used for V_1 and V_2 which are easily replaced for discrete changes in the mixture ratio.

ANALYSIS OF THE MIXING SYSTEM

Consider the system of Figure 2, in which two proportional fluid amplifiers modulate the flow of Fluids A and B. A fluid sensor, in the form of a venturi orifice, on the mixture line provides control to both the amplifiers. The control line on each amplifier has a variable resistor for changing or adjusting the mixture ratio. A preliminary analysis to determine the mixing characteristics of the system was conducted. The analysis is based on the following assumptions:

1. The supply heads for the two fluids remain constant.
2. Flow velocities through the system are low and the distances are short, therefore, the head loss due to friction will be neglected.
3. In the fluid amplifier the area change effects are small, therefore, the static pressure through the amplifier is considered constant. Also, experience has shown that the static pressure at the outlet ports of the amplifier is constant with variation in flow.
4. The flow through the amplifier outlet port is a linear function of the control flow and the outlet flow is zero for zero control flow.
5. The flow is considered incompressible and inviscid.
6. Mixing of the two fluids is homogenous.

Let the fluid amplifier S_1 (Figure 2) deliver Fluid A of mass density ρ_1 slugs/ft^3 at the rate of Q_1 ft^3/sec through the outlet O_1 to the junction M. Correspondingly, the fluid amplifier S_2 delivers Fluid B of mass density ρ_2 slugs/ft^3 at the rate of Q_2 ft^3/sec through the outlet O_2 to the junction M. After thorough mixing of the fluids at M, the mixture has a mass density of ρ slugs/ft^3 and flows at the rate of Q ft^3/sec through the line MZ such that the static pressure in the line is P_a lb/ft^2. The static pressure through the amplifier is assumed to be constant, therefore:

$$P_{c_1} = P_{O_1} = P_1, \text{ and } P_{c_2} = P_{O_2} = P_2;$$

where P_1 and P_2 are static pressures in the fluid amplifiers S_1 and S_2 respectively. Considering conservation of mass yields the relation:

$$\rho_1 Q_1 + \rho_2 Q_2 = \rho Q. \tag{1}$$

From Equation (1), the expression for the mixture density ρ is:

$$\rho = \frac{Q_1 \rho_1}{Q} (1 + \frac{\rho_2}{\rho_1} x), \tag{2}$$

where x is the mixture ratio Q_2/Q_1.

Writing Bernoullie's equation for points V and Z of the system,

$$\frac{P_v}{g\rho} + \frac{Q^2}{2gA_v^2} = \frac{P_a}{g\rho} + \frac{Q^2}{2gA^2} . \tag{3}$$

In Equation (3), P_v is the static pressure in lb/ft^2 at the venturi throat and A_v and A are the cross-sectional areas of the venturi throat and the mixture flow line respectively. From Equations (2) and (3), it can be shown that the static pressure at the venturi orifice V is,

$$P_v = P_a + \frac{\rho_1 Q_1^2}{2A^2} \left[(1 + x)(1 + \frac{\rho_2}{\rho_1} x)(1 - \frac{A^2}{A_v^2}) \right] . \tag{4}$$

For any mixture flow rate Q the flow through the control line C_1, considering only the valve loss, is

$$Q_{c_1} = C_{c_1} A_{c_1} \sqrt{(P_{c_1} - P_v)/\rho_1} = C_{c_1} A_{c_1} \sqrt{(P_1 - P_v)/\rho_1}\,, \tag{5}$$

where C_{c_1} is the valve loss coefficient corresponding to a given setting of the valve V_1 and A_{c_1} the cross-sectional area of the control line.*

Since it is assumed that the amplifier has linear characteristics, the output flow Q_1 is related to the control flow Q_{c_1} by

$$Q_1 = G_1 Q_{c_1}, \tag{6}$$

where G_1 is a constant for the amplifier S_1.

Hence from Equations (5) and (6), it can be written that

$$Q_1 = G_1 A_{c_1} C_{c_1} \sqrt{(P_1 - P_v)/\rho_1}\,. \tag{7}$$

Similarly, the expression for Q_2 will be

$$Q_2 = G_2 A_{c_2} C_{c_2} \sqrt{(P_2 - P_v)/\rho_2}\,. \tag{8}$$

where G_2 is a constant for the amplifier S_2, and A_{c_2} and C_{c_2} are the cross-sectional area of control line C_2 and the valve loss coefficient respectively.

Combining Equations (4), (7) and (8) yeilds the implicit expression for the mixture ratio as

$$x = \frac{G_2 A_{c_2} C_{c_2}}{G_1 A_{c_1} C_{c_1}} \sqrt{\frac{\dfrac{P_2 - P_a}{\rho_2} - \dfrac{\rho_1}{\rho_2} \dfrac{Q_1^2}{2A^2} \left[(1 + x)(1 + \dfrac{\rho_2}{\rho_1} x)(1 - \dfrac{A^2}{A_v^2})\right]}{\dfrac{P_1 - P_a}{\rho_1} - \dfrac{Q_1^2}{2A^2} \left[(1 + x)(1 + \dfrac{\rho_2}{\rho_1} x)(1 - \dfrac{A^2}{A_v^2})\right]}}\,. \tag{9}$$

For a practical application amplifiers S_1 and S_2 can be of identical design. For such a system x can be determined explicitly since

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*This coefficient is related to the conventional valve loss coefficient k by the relation $C_c = \sqrt{2/k}$.

$$P_2 = P_1, \; G_2 = G_1, \; A_{c_2} = A_{c_1},$$

and Equation (9) simplifies to

$$x = \frac{C_{c_2}}{C_{c_1}} \sqrt{\frac{\rho_1}{\rho_2}} \; . \qquad (10)$$

For this case the mixture ratio x varies linearly with the ratio of valve loss coefficients as shown in Figure 3.

Consider an example where fluids of the same density are mixed together. Assume that the valve on the control line of amplifier S_2 remains fully open while the opening of the valve on that of amplifier S_1 is varied. The mixture ratio for this example can be conveniently computed from Equation (10). Table 1 shows the results of such a computation. It can be seen from the table that the mixture ratio changes considerably by varying the valve opening on one of the amplifier's control line from fully open to 1/4 open.

SELECTION OF A SUITABLE FLUID AMPLIFIER

Proportional fluid amplifiers such as the beam deflector amplifier, vortex devices (like the vortex amplifier and the vortex fluid throttle), and the throat injection throttle possess flow modulating characteristics. Therefore, these devices can be conveniently used in metering the flow of fluids and have potential applications in the fluidic mixing systems.[2]

The vortex amplifiers are off-the-shelf items, and they can handle both gases as well as liquids, including non-newtonian fluids (like slurries). Some researchers have shown the feasibility of gas flow control using the vortex fluid throttle or the throat injection throttle. Displacement and vortex venturis are devices which are suitable for modulating liquid flows. These devices have the limitations that the output flow cannot be reduced to zero, and the control pressure must be greater than the supply pressure (usually 50% to 100% greater than the supply pressure).[2]

Proportional amplifiers, on the other hand, are capable of modulating the output flow from full flow to zero and are, therefore, more applicable for fluid mixing. The double leg elbow type of proportional amplifier seems best for the mixing application because of its high gain.[4] It should be pointed out here that such fluid amplifiers have been used on control systems only and thus have small flow handling capacities. Therefore, it was decided to develop a suitable double leg elbow amplifier for use in the fluidic mixing systems. The next section of the report describes the design, fabrication, and testing of the double leg elbow fluid amplifier capable of delivering 0-5 gpm of water.

Table 1. Variation of Mixture Ratio with the Control Line Valve Settings

Valve Setting on the Control Line of Amplifier		Valve Loss Coefficient Ratio * $\frac{C_{c_2}}{C_{c_1}} = \sqrt{\frac{k_1}{k_2}}$	Fluid Density Ratio ρ_1/ρ_2	Mixture Ratio $x = \frac{C_{c_2}}{C_{c_1}}\sqrt{\frac{\rho_1}{\rho_2}}$
S_1	S_2			
Fully open	Fully open	1	1	1
3/4 open	Fully open	2.46	1	2.46
1/2 open	Fully open	5.44	1	5.44
1/4 open	Fully open	11.23	1	11.23

*Reference 4

DOUBLE LEG ELBOW AMPLIFIER

The concept of the double leg elbow amplifier was originated at Giannini Controls Corporation and is described in detail in Reference 5. The operational principle underlying the amplifier is based upon the fluid dynamic phenomenon associated with the flow through a short radius elbow.[5,6] To understand the principle, consider the flow through a curved channel of Figure 4, in which the velocity of flow is sufficiently high to cause separation along the inner wall of the channel at point B. Corresponding to this flow configuration, let the velocity profile at the channel exit be represented by U_B. If by boundary layer control techniques such as by generating suction at the inner wall, the point of separation is moved to A, the velocity profile at the channel exit then would be represented by U_A. It can be seen from Figure 4, that large changes in the momentum flux through the exit of the channel can be achieved by moving the separation point from B to A. It should be realized, however, that all these changes can be accomplished by low energy flows such as are shown in Figure 5. One case of control shows the boundary layer removal by inducing suction at the inner wall, while the alternative scheme is to cause forced separation by the counterflow at the inner wall of the elbow or channel. Hence, the curved channel of Figure 4 with suitable design features can act as a fluid amplifier.

The double leg elbow amplifier shown in Figure 6 works on this principle. The flow through the active leg of the amplifier, in the form of a short radius elbow, is controlled by a low energy flow through the control port (which creates suction). Further, the flow through the passive leg of the amplifier combines with the flow through the channel at its exit and forms a combined jet. The combined jet depending upon the amount of control flow divides itself proportionally into the two output ports. The amplifier can be designed in such a way such that for no control flow the whole of combined jet passes through the output O_1, and for some maximum value of the control flow the jet passes through the output O_2. The purpose of the splitter vane in the device is to change the momentum flux at the channel exit by bleeding some of the flow through the port SV. The function of the spoiler on one of the walls is to avoid permanent attachment of the combined jet to the wall. The amplifier is a very high gain device. For example, double leg elbow amplifier mass flow gains of 220 have been obtained with air as the flow medium.

THE EXPERIMENTAL FLUID AMPLIFIER

Design

The experimental double leg elbow amplifier was designed with a flow handling capacity of 5 gpm of water. Based upon this flow rate, the amplifier's parameters were determined using fundamental fluid dynamic relationships. The active leg elbow radii were chosen (in this case:

$$\frac{\text{inner wall radius}}{\text{outer wall radius}} = \frac{1}{3})$$

such that the separation in the elbow will occur naturally. It was further assumed that 2.5 gpm of water flows through the active leg and 2.5 gpm flows through the passive leg. The flow Reynolds numbers through the amplifier passages were chosen in the range of 50,000 to have a strong combined jet formation from the interaction of the two inlet jets. The control on the amplifier was assumed to be of the boundary layer removal type, caused by inducing suction in the control port. The splitter vane angles were determined from the momentum exchange considerations between the two inlet jets. The maximum deflection of the combined jet corresponding to the maximum control flow was assumed to be about 15°. Table 2 lists the values of all the important design parameters of the amplifier.

Fabrication

The amplifier consists of three major components: the top and bottom cover plates, and the middle plate with the flow passages cut in it. The middle is made of aluminum and the flow passages in it were machined by milling process. The cover plates for the amplifier are made of transparent plexi-glass sheets to facilitate the flow visualization during the test. The cover plates and the middle plate of the amplifier are shown in Figure 7. Before assembling the amplifier, the two surfaces of the aluminum plate were covered with a thin layer of silicon grease to prevent leakage during operation. The assembled fluid amplifier ready for testing is shown in Figure 8.

EXPERIMENTAL PROGRAM

An experimental program to determine the mixing characteristics of the fluidic mixing system was designed. A major portion of the program was directed towards developing a suitable double leg elbow fluid amplifier to deliver 0-5 gpm of water. The aim of the program is to mix hot and cold water in the desired ratios at varying or constant mixture flow rates. This section of the report describes the test set up including instrumentation used and the test procedure during the program.

Test Setup

The experiments were conducted in the Mechanical Systems Laboratory at NCEL. Regular tap water was used as the test fluid under carefully controlled flow and pressure conditions. All experiments were conducted under continuous flow conditions so that sufficient time was available for stabilization of all flows and instrument readings.

Table 2. Parameters of the Designed Double Leg Elbow Fluid Amplifier

1. Active Leg

Width	1 inch
Height	1/4 inch
Inner wall radius	1/2 inch
Outer wall radius	1-1/2 inch
Cross-sectional area	0.25 inch
Designed flow	2.5 gpm or 0.334 ft^3/min
Reynolds number at the designed flow*	51,500

2. Passive Leg

Width	3/4 inch
Height	1/4 inch
Cross-sectional area	0.188 $inch^2$
Designed flow	2.5 gpm or 0.334 ft^3/min
Reynolds number at the designed flow*	51,500
Angle between active leg and passive leg	80°

3. Control Port

Width	1/16 inch
Height	1/4 inch
Cross-sectional area	0.0156 $inch^2$
Location	30° from the place of curving of inner wall of the elbow
Type of control	Suction

4. Output Ports

Width	1-1/2 inch
Height	1/4 inch
Number of Ports	2
Cross-sectional area	0.376 $inch^2$
Splitter location	6 inches from the point of intersection of the two inlet ports.

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*Kinematic viscosity of water at $60^{\circ}F$ is taken as 5.19×10^{-6} ft^2/sec.

The general arrangement of flow lines and various measuring instruments for the test setup are shown in the schematic of Figure 9. Cold water is throttled to the 5-25 psig range by means of a pressure regulator on the line and further adjustment of the supply flows is possible by the hand controlled valves provided on the lines. A hot water heater provided hot water which was also throttled to the 5-25 psig range by a pressure regulator on the line. The control flow to the amplifier was provided by means of an eductor system capable of creating suction on the line. The photograph of the actual setup is shown in Figure 10.

Test Instrumentation

Volume flow rates, pressures, and temperatures of the fluids were measured during the test. Further, to study the flow pattern of water through the fluid amplifier, flow visualization techniques were used in the program. The various instruments or equipment used for these measurements are described below:

(1) Volume Flow Rates. Supply, control, and output flow rates were measured by rotameters.

(2) Pressures. Static and differential pressures were measured by conventional pressure gages and monometers.

(3) Temperature. The temperature of incoming hot and cold water and that of the outgoing mixture were measured by thermometers.

(4) Flow Visualization. Throughout the test program visual studies were conducted by injecting ferric oxide solution into the active leg supply port of the fluid amplifier and viewing the flow pattern color which can be varied simply by changing the amount of injectant into the supply port. Photographs of the flow pattern were taken by mounting a camera on the test setup.

Test Procedure

Tests were designed to develop a suitable double leg elbow amplifier. A series of tests were conducted by varying the flow through the active and passive legs of the amplifier at varying control flow. At the end of each test series the appropriate changes in the amplifier's parameters (such as size and location of the control port and splitter vane) as concluded from the flow visualization studies were made. This iterative process was continued until the amplifier was functioning as a proportional device.

The amount of ratio and flow through the active and passive legs of the amplifier for its optimum operation were recorded. The amplifier's characteristics were determined by recording the output flow as a function of control flow.

Test Results

Modified version of the double leg elbow amplifier functioning as a proportional device is shown in Figure 11. Data obtained during the test are listed in Table 3. The amplifier's flow characteristics are shown in Figure 12. The optimum performance of the amplifier occurs at a ratio of the passive leg flow to the active leg flow of 5.0. At the optimum performance the amplifier modulates the flow of water to the mixing junction from 0.50 to 4.3 gpm.

Flow pattern through the amplifier for no control flow is shown in Figure 11, and for maximum control flow is shown in Figure 13.

DISCUSSION

There was a considerable amount of fluctuation in the outflow from the amplifier. This flow fluctuation may be attributed to several effects. First, and possibly the most predominant, was the turbulence in the inlet ports caused by the high Reynolds numbers (51,500). Second, the variations in the supply pressures might have caused outflow fluctuations. Other possible sources of flow fluctuations were improper location of the splitter at the output ports of the amplifier which resulted in the edge tone effect.* Additional testing is required to eliminate fluctuations of the output flow.

CONCLUSIONS

Test results have shown that the designed fluid amplifier is capable of modulating water flow from 0-5 gpm. However, some problems still exist in that the amplifier delivers a fluctuating output flow. Also, the flow characteristics are not as linear as desired.

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*Edge Tone Effect: When a jet of fluid impinges on a wedge, the jet oscillates about the wedge tip. The jet sheds a vortex on one side of the wedge, moves to the other side and sheds a vortex, then moves back and continues the process.

Table 3. Test Data at Optimum Performance

Supply Pressure = 12 psig

Flow through the active leg of the amplifier = 1.16 gpm

Flow through the passive leg of the amplifier = 5.8 gpm

Run Number	Flow Through the Control Port gpm	Outflow to the Mixing Junction gpm
1	0	0.50
2	0.30	1.00
3	0.50	1.30
4	1.00	4.30

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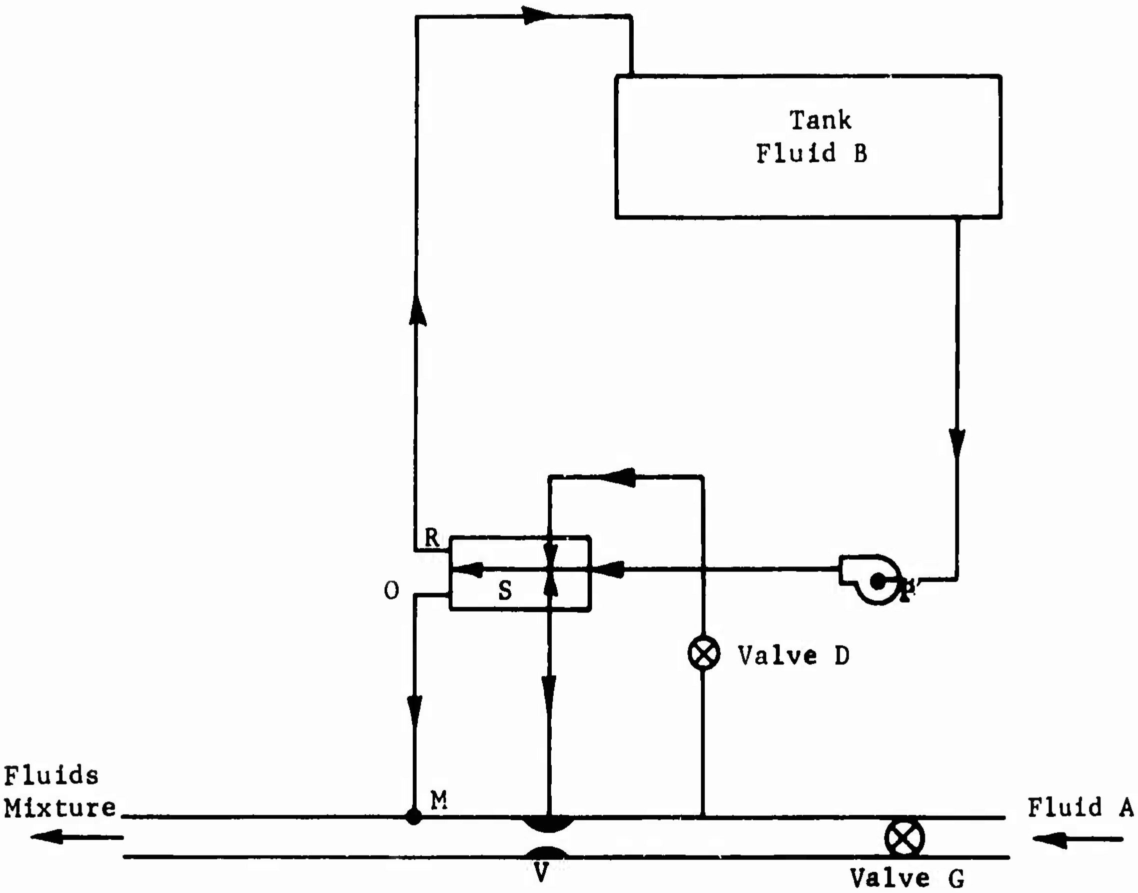


R = return line to the tank

O = mixing line

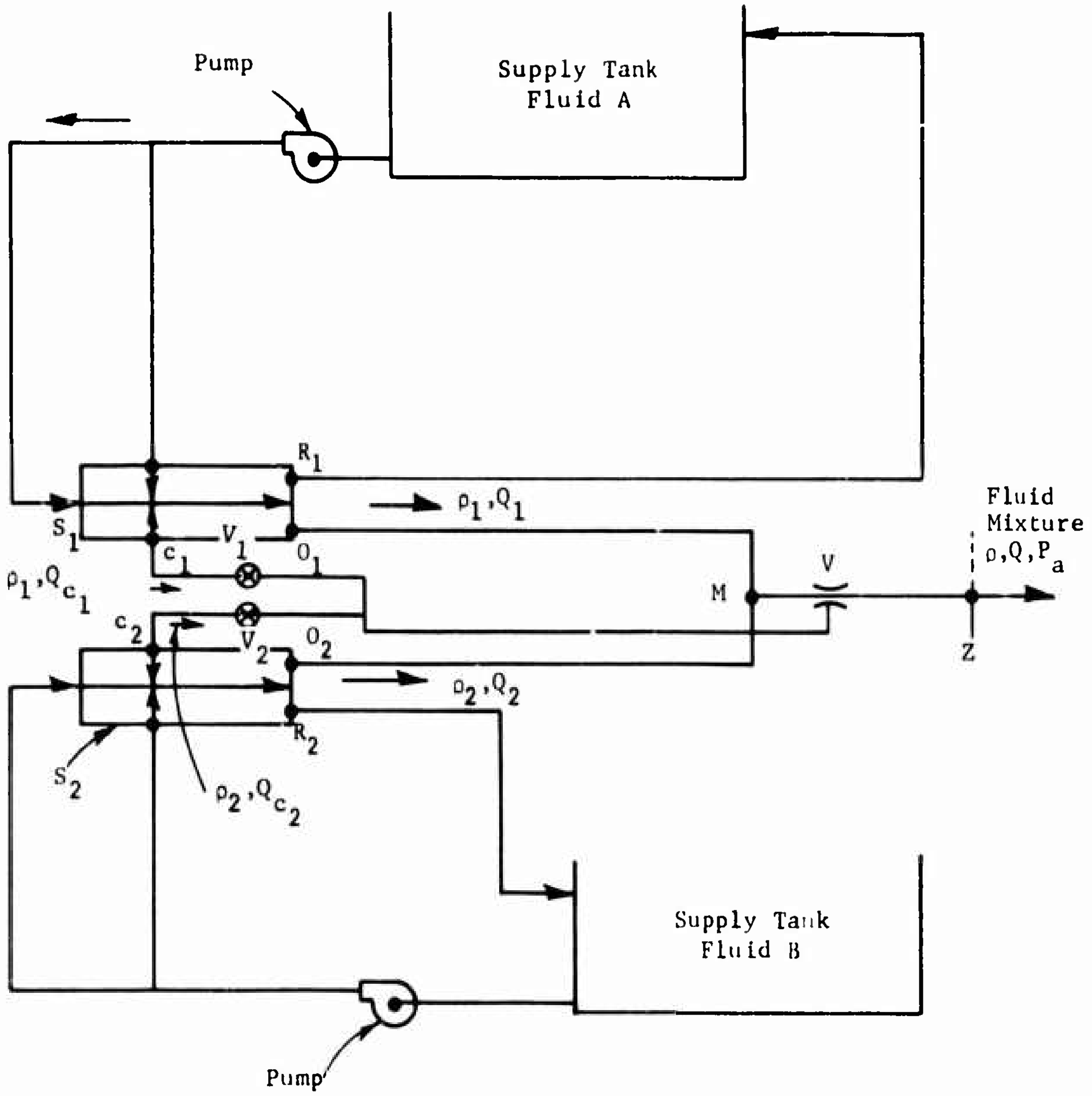
V = venturi orifice

S = fluid amplifier

P = pump

M = mixing junction

Figure 1. Mixing system for two fluids using one proportional fluid amplifier.



1 = subscript referring to Fluid A
2 = subscript referring to Fluid B
c_1, c_2 = subscript referring to control ports on the amplifiers
R = return line to the supply tank
M = mixing junction
V = venturi orifice
S = fluid amplifier
MZ = the mixing line
O_1, O_2 = the outlet port to the mixing junction
R_1, R_2 = the outlet port to the return lines

Figure 2. A complete fluidic system for mixing two fluids.

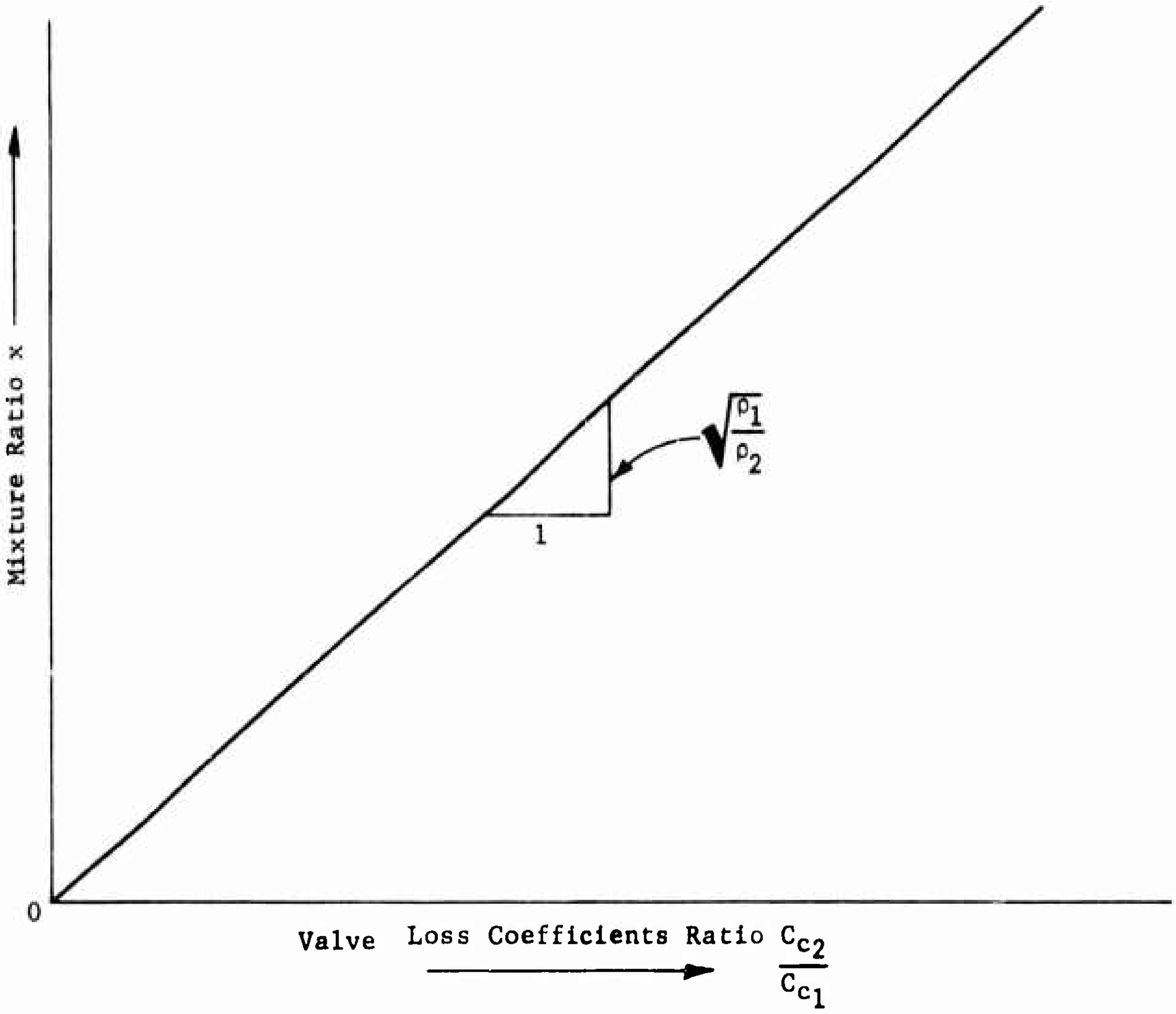


Figure 3. A plot of mixture ratio versus valve coefficients ratio for a practical mixing system.

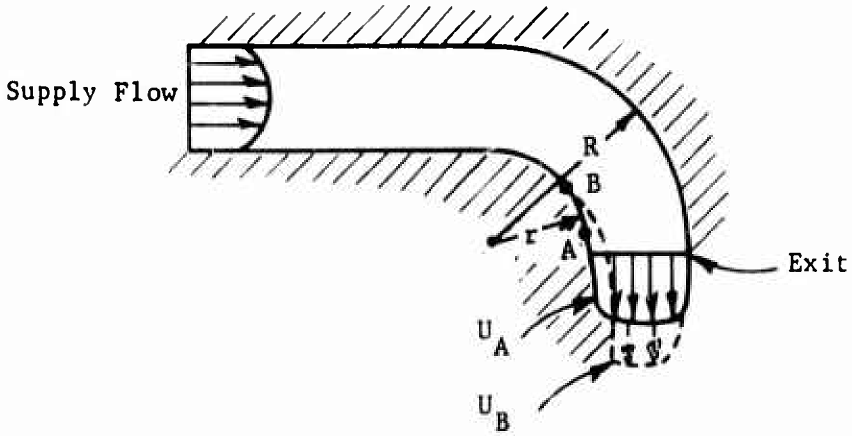


Figure 4. Separated flow in a curved channel.

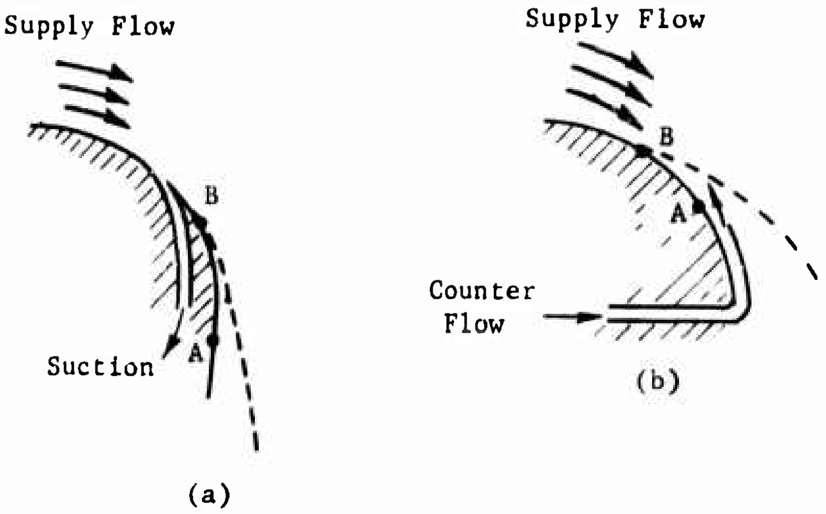


Figure 5. Various methods of boundary layer control.

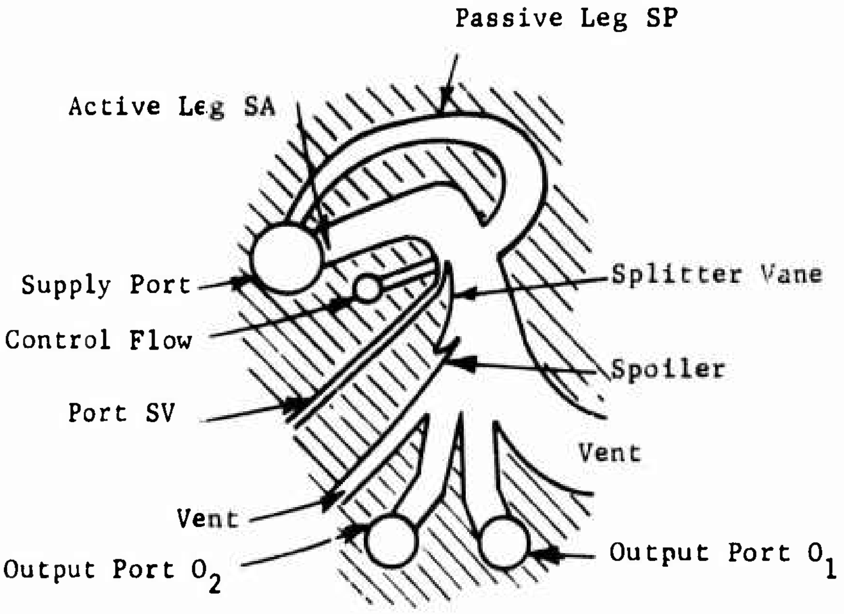


Figure 6. Double-leg elbow amplifier.

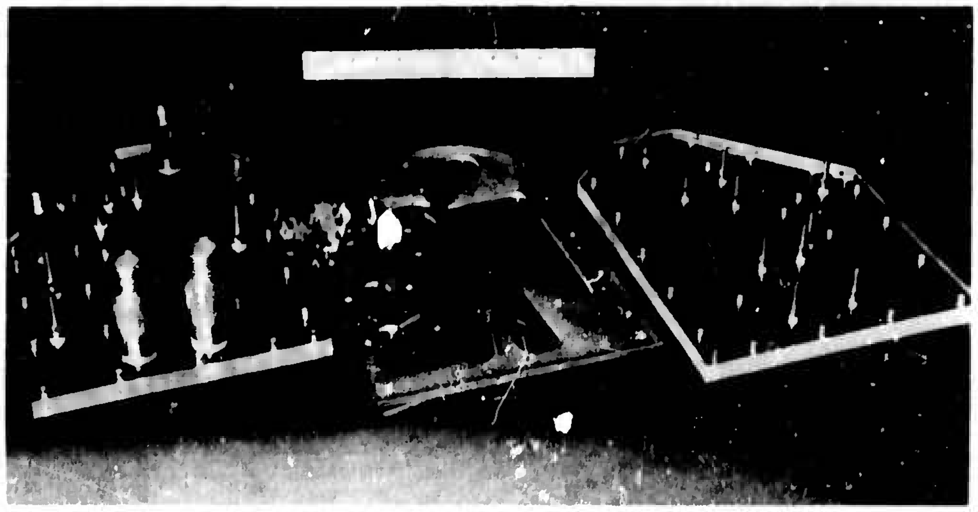


Figure 7. Amplifier's Components.

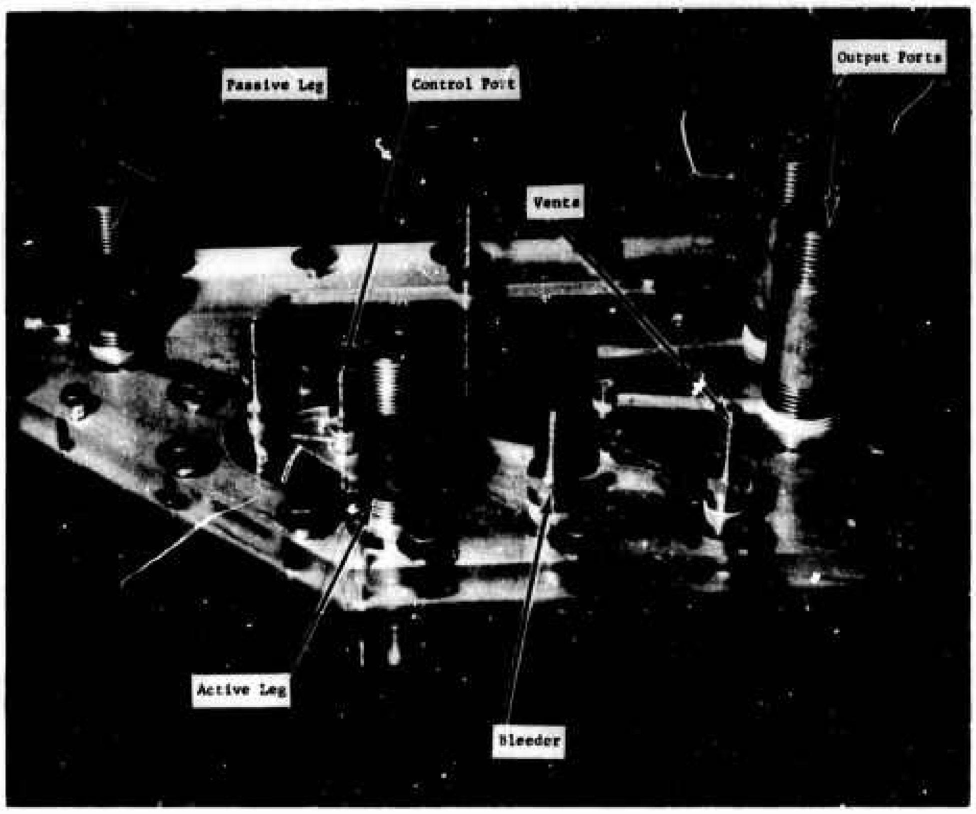


Figure 8. Assembled fluid amplifier before tests.

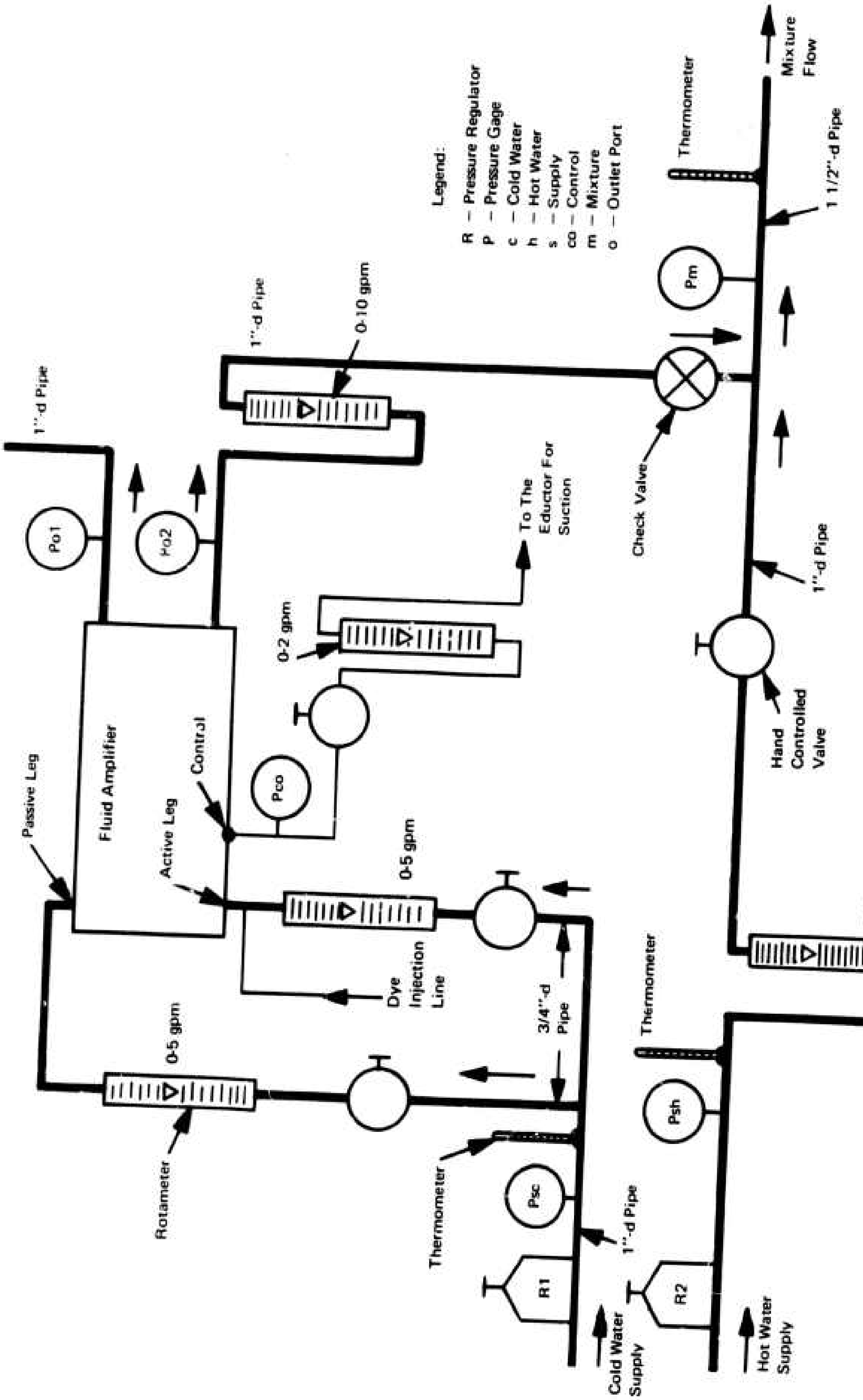


Figure 9. Schematic of the test setup.

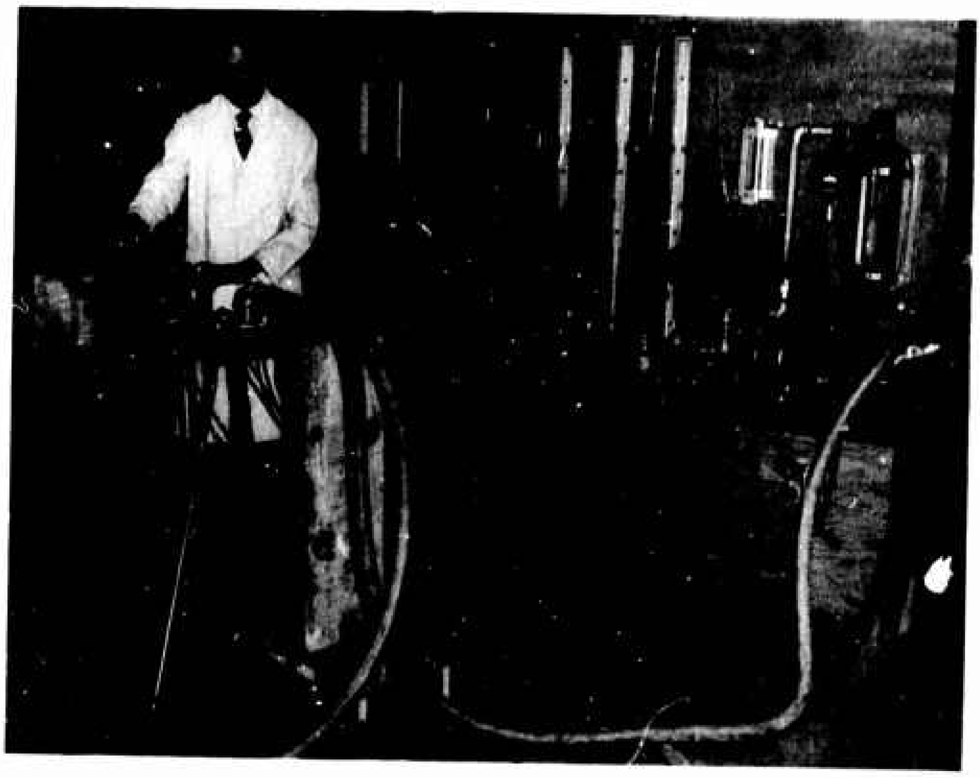


Figure 10. Actual test setup.

Figure 11. Flow pattern through the amplifier with no control flow.

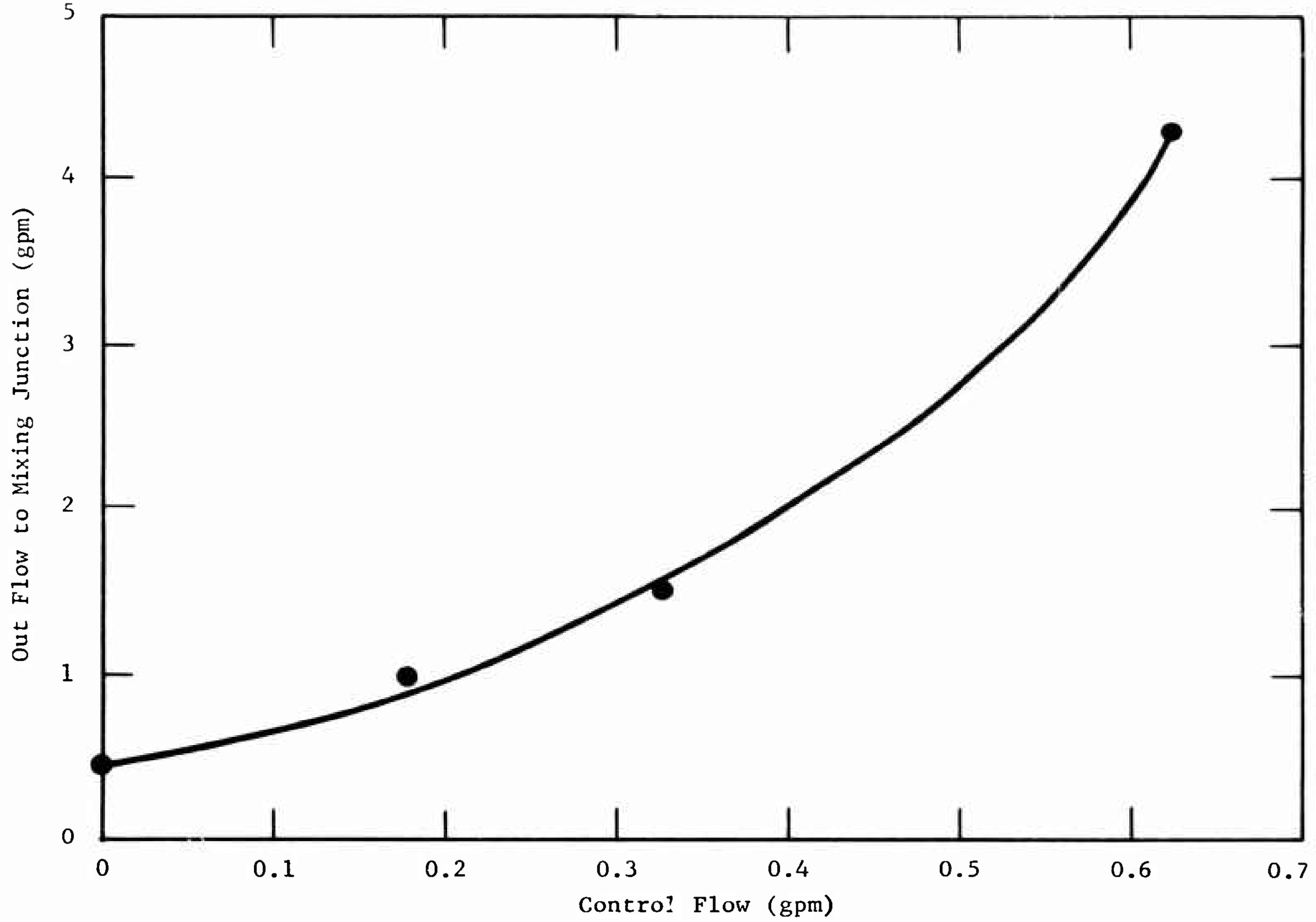


Figure 12. Amplifier's output flow characteristics.

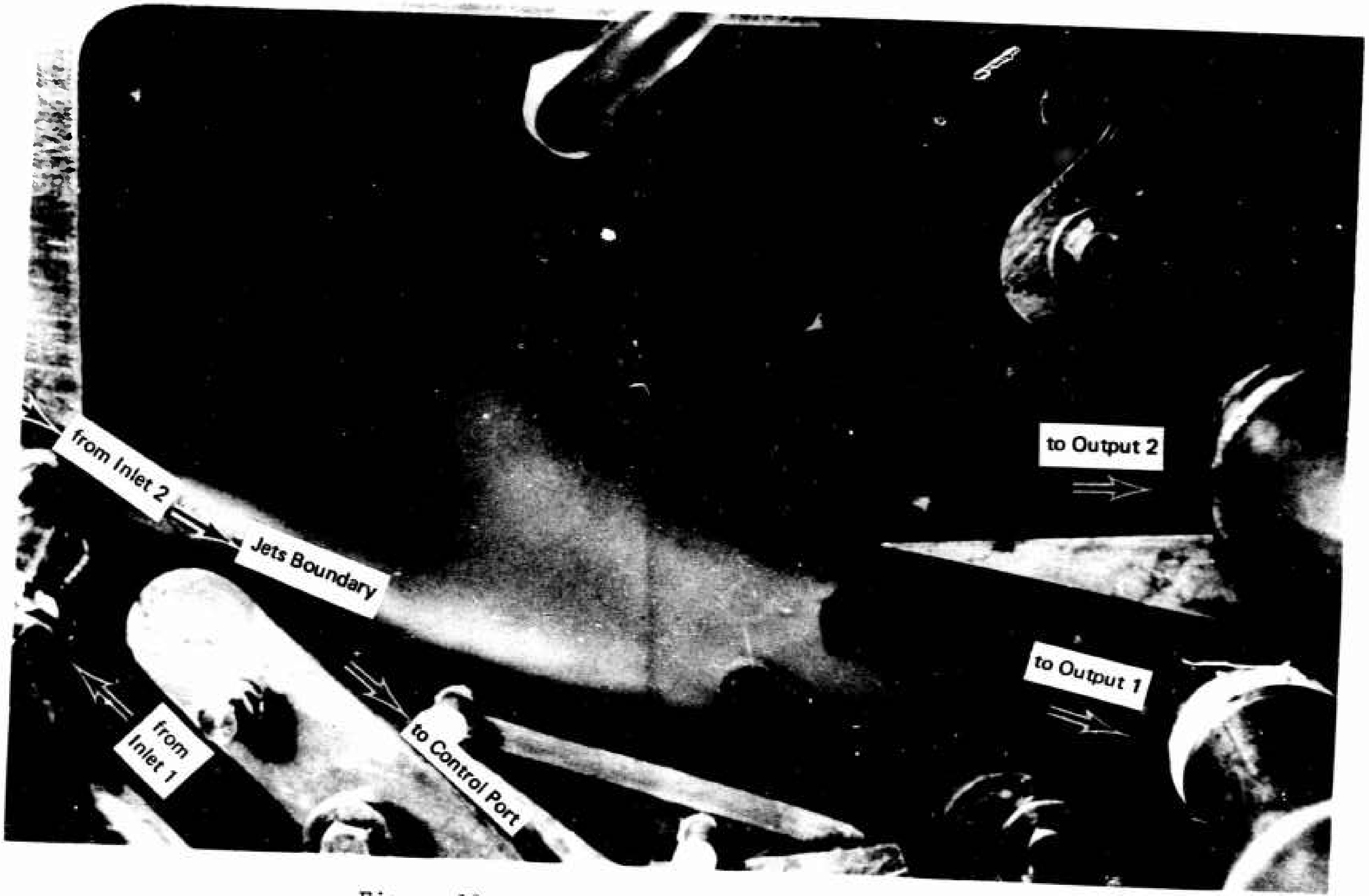


Figure 13. Flow through the amplifier with maximum control flow.

UNCLASSIFIED
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Port Hueneme, California 93043

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UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
A FLUIDIC SYSTEM FOR MIXING TWO FLUIDS - DEVELOPMENT STUDY

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*
D. Pal

6. REPORT DATE
February 1971

7a. TOTAL NO. OF PAGES
24

7b. NO. OF REFS
6

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. ZF 38.512.001.005

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TN-1150

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Director of Navy Laboratories
Washington, D. C. 20360

13. ABSTRACT

Results of a study on the use of proportional fluid amplifiers for the mixing of two fluids are presented. The system proposed is considered capable of mixing fluids in varying mixture ratios. For this application, the fluidic device promises to be superior to conventional mechanical flow modulating devices. The fluidic mixing system being tested uses a double leg elbow amplifier and is designed for mixing hot and cold water.

DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6801

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fluidic amplifiers						
Mixing						
Water						
Fluid flow						
Fluidics						