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FLUID AMPLIFICATION

10. Use of the Hydraulic Analogy in the Study of Fluid-Interaction Devices

Ralph G. Barclay

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15 April 1963

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HARRY DIAMOND LABORATORIES
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NOMENCLATURE

a	velocity of sound
b	diffuser exit opening
b_R	distance to stream reattachment point
C	speed of wave propagation
c_p	specific heat at constant pressure
C_{PR}	pressure-recovery coefficient ($C_{PR} = \frac{P_2 - P_1}{q_1}$)
d	depth at point of interest
d_o	stagnation water depth
d_r	water depth recovered in diffuser
d_t	water depth in throat
g	acceleration due to gravity(32.2 ft/sec^2)
g_c	gravitational conversion factor ($32.2 \frac{\text{lb - ft}}{\text{lb - sec}^2}$)
ℓ_R, ℓ_L	wall lengths
M	Mach number
M_x	Mach number upstream of normal shock
M_y	Mach number downstream of normal shock
p	static pressure at point of interest
P_p, P_c, P_c'	power-jet and control-jet pressures
p_e	exit static pressure
p_o	stagnation or total pressure
p_x	static pressure upstream of normal shock
p_y	static pressure downstream of normal shock
P_1	static pressure in the throat
P_2	static pressure at the end of diffuser
q_1	dynamic pressure
S_L, S_R	wall set-back distances

T	absolute temperature at point of interest
T_o	absolute stagnation temperature
u	velocity component in the x-direction
v	velocity component in the y-direction
V	velocity
w	nozzle width
x	diffuser length
β_L, β_R	wall angles
γ	ratio of specific heats
θ	diffuser half-angle
ρ	mass density

ABSTRACT

The advantages of using the hydraulic analogy to study compressible gas flow in fluid interaction devices are discussed. The mathematical basis of the analogy is summarized, and limitations in its use are pointed out. Various practical aspects concerning operation of an analogy facility are reviewed.

Four hydraulic-analogy studies are briefly described: subsonic diffuser performance, three-stage closed-system bistable fluid-flow amplifier performance, quantitative measurement of switching flow required by a bistable fluid amplifier, and blocked-output-channel and stream-attachment characteristics in fixed and adjustable models of bistable elements.

Abstracts of seventeen references regarding the theory and application of the hydraulic analogy are given.

1. INTRODUCTION

Early interest in fluid interaction devices anticipated that major military applications would be made using compressible gases as the working fluid. Since the gross effect of design parameters on the complicated interacting flow was largely unknown at that time, basic investigations were at first necessary.

The velocity of flow in fluid interaction devices makes it difficult to observe flow in direct tests of models using compressible gas. Also, it is difficult to obtain important measurements without significantly interfering with the flow, since the devices are small. Therefore, many of the early basic investigations used the hydraulic analogy. Analogous water flows are slower by a factor of 1000, so that the effects of various operations on the flow can be easily seen. Models of the devices can be simply made and modified permitting the investigation of radically new design concepts with ease. The basic experimental equipment, the water table, is inexpensive and easy to instrument. The models can be easily inserted, tested, modified, and retested.

Since the analogy is imperfect in many ways, its reliability in predicting results for compressible gas requires an appraisal with respect to each new use. Such an appraisal was made for fluid interaction devices and is the topic of the first part of this report. In the second part of this report, several applications of the hydraulic analogy to determine the behavior of compressible gases in several fluid interaction devices are described. General comments regarding the design requirements for water tables used in fluid interaction studies, methods of visualizing flow, methods of making model fluid interaction devices, available instrumentation, etc., are covered in the appendixes.

2. BACKGROUND

Fluid interaction devices are those in which one fluid stream (power stream) is controlled or directed by another fluid stream (control stream). They differ from such fluid controlling devices as valves or vanes in that no moving mechanical parts are required. The power stream generally contains more flow and energy than the control stream.

Fluid interaction devices that have been developed include fluid amplifiers and fluid bistable switches (ref 1). The cross section of a fluid amplifier is shown in figure 1. The device is typically made from brass stock cut into the shape shown, and sandwiched between two parallel cover plates. The area enclosing P_p represents a closed volume into which air is introduced by a connecting passage drilled through one of the cover plates.

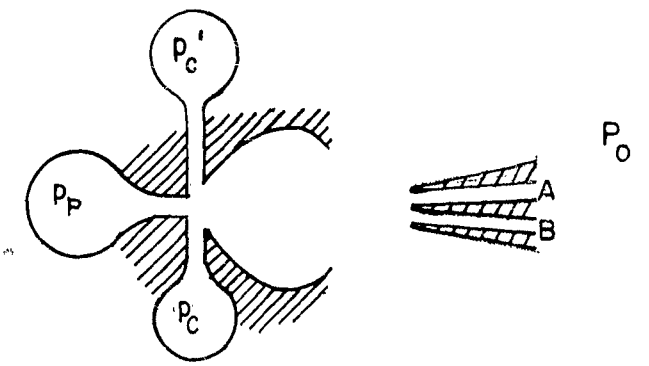


Figure 1. Basic fluid amplifier

In operation, a constant power-jet pressure P_p results in a constant flow called the power-jet flow, which issues from the nozzle. This flow is directed toward the right in figure 1. The splitter is positioned so that the flow is divided equally between A and B.

An input signal may be provided by introducing a signal across the controls P_c, P_c'. This control flow impinges on the power-jet flow and deflects it, so that the flow entering A differs from that entering B. Using the two output flows, a differential flow (the amplifier output) is obtained which is proportional to the input signal. Pressure amplification may also be obtained.

When the first amplifiers were built, it was noticed that the power stream tended to attach itself to the side wall (ref 2). In proportional amplifiers, this effect is prevented by setting back the sidewalls.

The attachment characteristic was applied in the fluid bistable switch (fig. 2). In this element, the control jet deflects the power jet to one side or the other, and, once the shift is made, the jet remains attached. The attachment is maintained until the opposing control jet deflects it to the other wall.

The operation of fluid interaction devices depends to a large extent on their geometry. Mathematical analysis of the steady-state condition

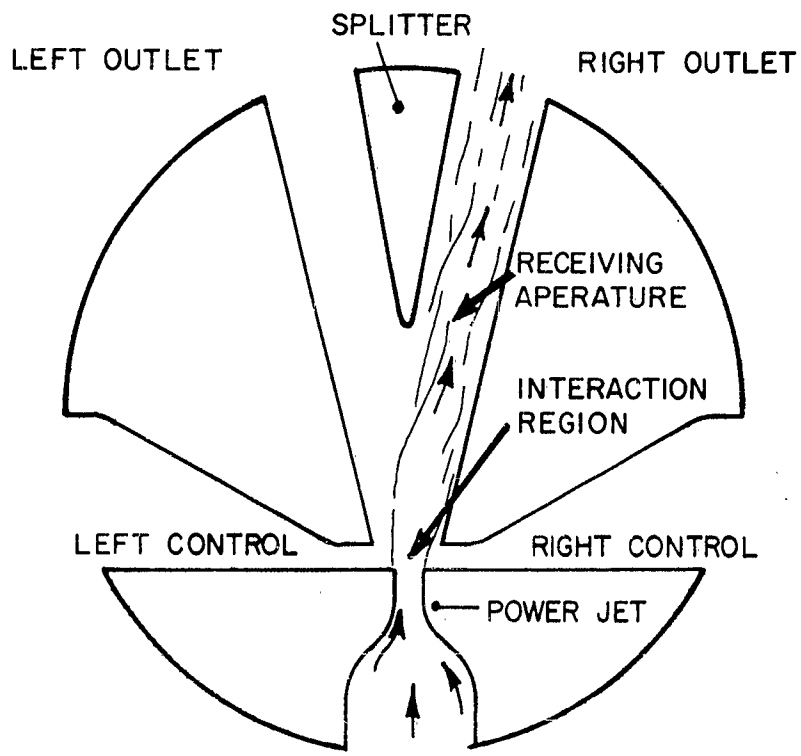


Figure 2. Diagram of fluid bistable element

is difficult, and time dependent situations, which are the norm, are much more so. Moreover, fluid flow systems are inherently distributed-parameter systems, which are not easy to analyze mathematically. Consequently, the early studies that led to the development of fluid interaction devices were largely experimental, and the most convenient and adaptable method of making the studies for reasons previously mentioned, were based on the hydraulic analogy.

3. THE HYDRAULIC ANALOGY

The usefulness of the hydraulic analogy in analyzing compressible gas flows in fluid interaction devices might be grossly stated as follows: The two-dimensional flow of a compressible gas may be determined by studying the flow of liquid (usually water) in an open channel of the same configuration and at the analogous velocity (at the same Mach number). While the Mach number of the compressible gas is in reference to the speed at which a pressure wave is propagated, the "Mach" number

of the liquid analog is referenced to the speed at which transverse gravity waves are propagated. The depth of liquid with a free surface is the analog of temperature or of density in the compressible gas. Therefore, these flow parameters of a compressible gas may be determined by measurement of flow velocity, depth, etc. of a liquid model, and the effect of design parameters may be easily determined by modification of flow or channel configuration. The flow pattern may be determined by direct observation of the model.

Figure 3 is a diagram of the HDL water table with the water flow produced by an impeller. When a nozzle section and a test model are placed on the flow surface, the water upstream of the nozzle represents the stagnation or reservoir section. The depth d of the water is measured at various points of interest on the flow surface.

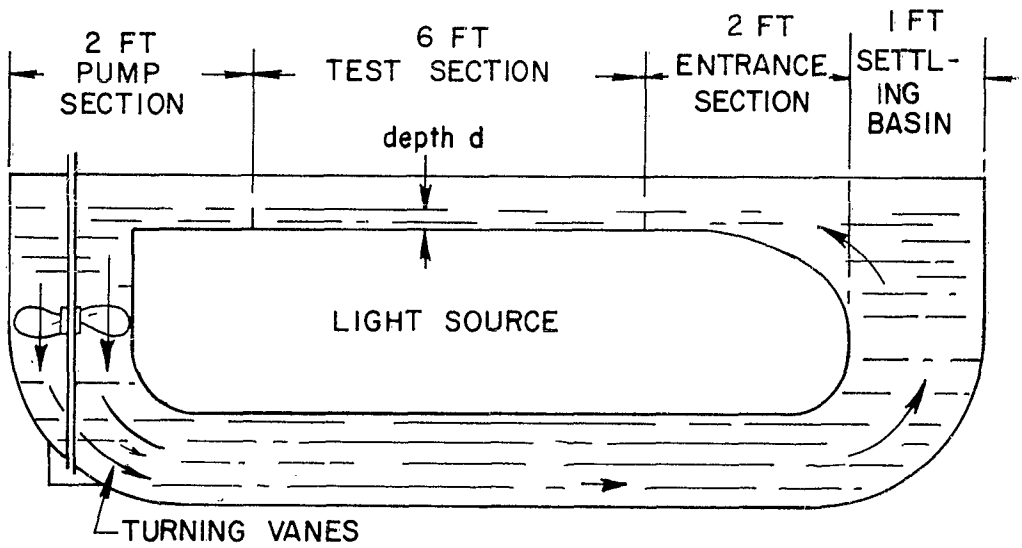


Figure 3. Diagram of HDL water table, side view.

3.1 Mathematical Basis

The mathematical basis of the analogy requires a much more strict and limiting statement, which is, that the hydraulic analogy is based on the similarity of the equations of motion for two-dimensional, irrotational, isentropic flow of a perfect gas with a specific

heat ratio of 2.0, and the equations of motion for two-dimensional, irrotational, frictionless flow of an incompressible liquid with a free surface. The correspondence of these equations is summarized as follows.

The energy equations for water and gas (ref 3) are used to obtain the velocity of the water and gas at any given point. For water, the velocity is:

$$V^2 = 2g\ (d_o - d) \tag{1}$$

where

d_o = stagnation water depth

d = depth at point of interest

g = acceleration due to gravity = $\frac{32.2\ \text{ft}}{\text{sec}^2}$

and

$$V_{max} = \sqrt{2gd_o} \tag{2}$$

For a gas, the velocity is:

$$V^2 = 2g_c\ c_p\ (T_o - T) \tag{3}$$

where

T_o = absolute stagnation temperature

T = absolute temperature at point of interest

g_c = gravitational conversion factor = $\frac{32.2\ \text{lbm-ft}}{\text{lbf-sec}^2}$

c_p = specific heat at constant pressure

and

$$V_{max} = \sqrt{2g_c\ c_p\ T_o} \tag{4}$$

Equating V/V_{max} for water and gas,

$$\frac{d}{d_o} = \frac{T}{T_o} \tag{5}$$

A further condition for the analogy may be derived from the equations for continuity. For water, the continuity equation is:

$$\frac{\partial(ud)}{\partial x} + \frac{\partial(vd)}{\partial y} = 0 \tag{6}$$

where

u = velocity in the x direction

v = velocity in the y direction

d = depth of the water

For two-dimensional gas flow, the continuity equation is

$$\frac{\partial(u\rho)}{\partial x} + \frac{\partial(v\rho)}{\partial y} = 0 \tag{7}$$

where

ρ = mass density of the gas.

From these two equations, the following may be derived:

$$\frac{d}{d_o} = \frac{\rho}{\rho_o} \tag{8}$$

Combining (5) and (8) yields:

$$\frac{d}{d_o} = \frac{T}{T_o} = \frac{\rho}{\rho_o} \tag{9}$$

However, for adiabatic insentropic gas flow,

$$\frac{\rho}{\rho_o} = \frac{T}{T_o}^{1/(\gamma-1)} \tag{10}$$

where γ is the ratio of specific heat at constant pressure to specific heat at constant volume. Consequently, to make eq (9) consistant with eq (10), γ must be equal 2.0, and since the isentropic pressure-density relationship is

$$\frac{p}{p_o} = \left(\frac{\rho}{\rho_o}\right)^{\gamma} \tag{11}$$

then

$$\frac{p}{p_o} = \left(\frac{\rho}{\rho_o}\right)^{2} \tag{12}$$

The velocity C, for waves in water that are long compared with the depth is given approximately by the equation

$$C = \sqrt{gd} \tag{13}$$

while the velocity a, for sound waves in gas is given by the expression

$$a = \sqrt{\frac{\gamma p}{\rho}} \tag{14}$$

The Mach number M of gas velocities is defined as

$$M \equiv \frac{V}{a} \tag{15}$$

hence the analogous Mach number for liquid flow is

$$M = \frac{V}{C}$$

Substituting from (1) and (13), this becomes

$$M = \frac{\sqrt{2g(d_o - d)}}{\sqrt{gd}} = \sqrt{\frac{2(d_o - d)}{d}} \tag{16}$$

In summary, comparing the flow of liquids with that of a hypothetical gas for which $\gamma = 2$, the following quantities may be equated:

Liquid Flow	Gas Flow
Water depth ratio, d/d_o	Temperature ratio, T/T_o
Water depth ratio, d/d_o	Density ratio, ρ/ρ_o
Water depth ratio squared, $(d/d_o)^2$	Pressure ratio, P/P_o
Mach number $\sqrt{2(d_o-d)/d}$	Mach number, V/a

3.2 Appraisal

In investigating real compressible gas flows in fluid interaction devices using the hydraulic analogy, a number of the assumptions are violated, and the analogy does not include certain significant flow parameters. The results of tests using a liquid model must therefore be interpreted accordingly. An appraisal that applies in many respects and that is the basis of much of the following discussion is given by A. H. Shapiro (ref 4).

3.2.1 Viscosity

The analogy relates inviscid gas flow to inviscid liquid flow. In studying the behavior of real gases by using a hydraulic model, this requirement is violated. However, the violation is mitigated somewhat by the presence of viscosity in both the gas and the liquid. For example, it is possible to study the attachment of a jet to a side wall with a liquid model, which would not be possible if the liquid were inviscid.

The disadvantage arising from a liquid's viscosity is that it distorts energy losses and the velocity distribution of flow. The drag of the bottom on the flowing liquid reduces the velocity in the deeper layers of flow and a churning or tumbling action can result. This was most apparent in the tests of hydraulic models of subsonic diffusers (sec. 4.2). A relatively shallow, high-velocity stream has a tendency to undercut a slower stream instead of producing a more orderly mixing. In some fluid amplifier models, the bottom drag results in flow in one direction near the surface of the water and in the opposite direction near the bottom. In supersonic work with hydraulic models, the shallow water depth necessary for proper wave action accentuates the bottom drag. Waves are attenuated much more quickly than in the analog gas.

3.2.2 Vertical Motions

In the analog, the liquid flow is assumed two-dimensional. For the subsonic case where relatively large models can be used, the vertical-velocity components in the liquid seem to be small enough to ignore, and the flow is effectively two-dimensional. For supersonic flow, vertical accelerations in the liquid are relatively large due to the abrupt transitions inherent in supersonic flow. In combination with the free surface, this tends to reduce the accuracy of computed velocities and pressures.

3.2.3 Wave Propagation

In a gas, the velocity of propagation of sound waves or small pressure disturbances is effectively independent of wavelength. This is not true in the case of transverse water waves of which there are two types: the gravity waves, which are dependent on the depth of the water, and the capillary waves which are primarily a surface effect independent of depth. Figure 4 shows the speed of

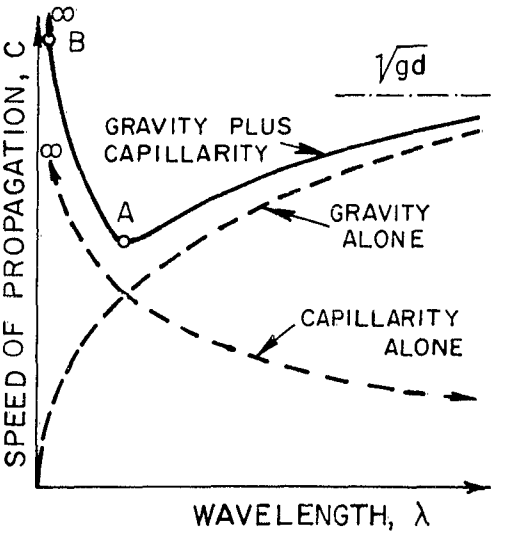


Figure 4. Propagation speed versus wavelength for combined gravity and capillary waves. The solid curve refers to specific values of the water depth, density, and surface tension. (Credit: A. H. Shapiro)

propagation as a function of wavelength for both types of waves and a combination of both types. Figure 5 shows the speed of propagation

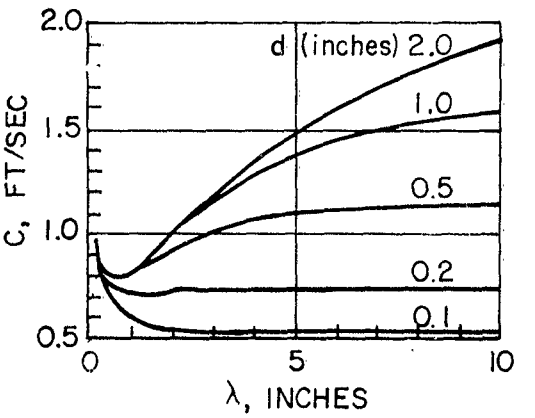


Figure 5. Propagation speed versus wavelength for combined gravity and capillary waves. Effect of water depth. Curves refer to pure water at standard temperature.
(Credit: A. H. Shapiro)

of a combined wave as a function of wavelength with water depth as a parameter. From this curve it may be seen that choosing a water depth of 0.2 in. will result in obtaining a wave velocity substantially independent of wavelength. Consequently this depth is usually chosen for simulating supersonic experiments. Where waves of two or more speeds exist the multi-ripple effect illustrated in figure 6 will be observed.

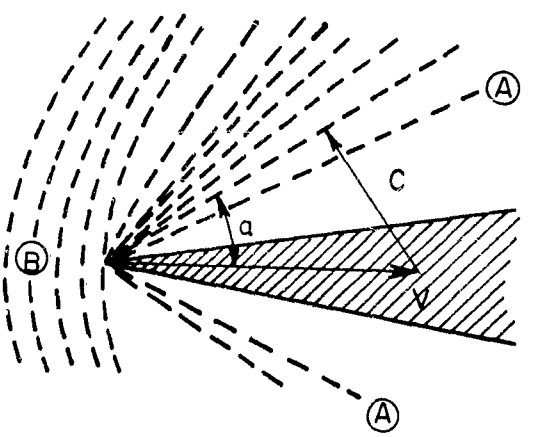


Figure 6. Schematic wave pattern for supersonic flow past wedge. "A" represents wave of minimum propagation speed. "B" represents head ripples, the propagation speed of which equals the speed of flow
(Credit: A. H. Shapiro)

3.2.4 Shocks

Under certain conditions, the transverse water waves combine to produce wave fronts that are the hydraulic analog of Mach

lines and relatively weak oblique shock waves. It is also possible to produce in the water table a phenomenon called the hydraulic jump which resembles a normal shock because, in both, there is a significant involvement of non-isentropic processes, whereas the analogy is based on isentropic processes. The pressure ratio produced by a hydraulic jump is not the same as that produced by the normal shock although they differ by a surprisingly small amount (fig. 7). The term pressure ratio as used here is the ratio p_y/p_x where p_x and p_y are, respectively, the pressures upstream and downstream of the normal shock or the hydraulic jump at points marked x and y in figure 7. For the hydraulic analogy of the shock, the pressure ratio is given by the square of the ratio of the depths of points x and y.

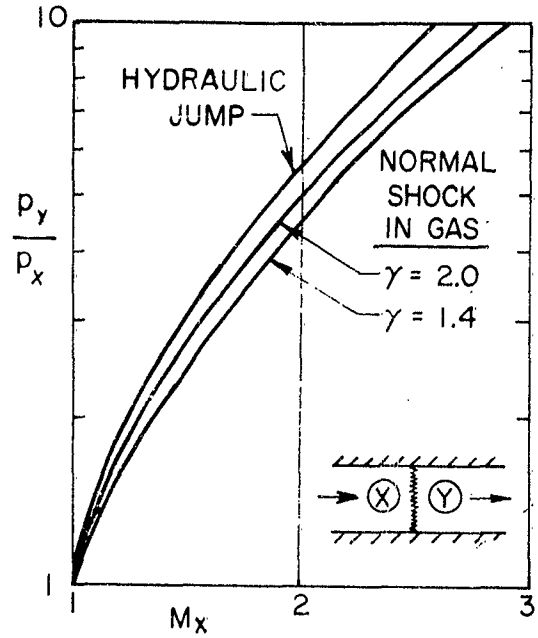


Figure 7. Pressure ratio for hydraulic jump and for normal shock in gas. Effect of specific-heat ratio. (Credit: A. H. Shapiro)

While not faithfully representing a normal shock, the hydraulic jump none-the-less is a fluid-flow phenomenon of the same general nature as the normal shock. In both cases, a disturbance exists downstream that cannot propagate upstream due to the high velocity of the oncoming flow. It is possible to illustrate normal shock action using the hydraulic model and thus gain some insight for qualitative purposes.

3.2.5 Surface Tension

Surface tension causes the water surface to act as a membrane and makes possible capillary waves. Capillary waves are generally of small wavelength and high speed and tend to obscure the waves of interest. In subsonic hydraulic experiments they may be disregarded, or else reduced by use of wetting agents or detergents.

In supersonic hydraulic experiments, capillary waves help produce an approximation of constant velocity with wavelength

as shown in figure 4. Very short high-velocity capillary waves are still not part of the analogy, however, and tend to clutter shadowgraph pictures.

3.2.6 Ratio of Specific Heats

In the development of the analogyin sec. 3.1, it was found that the compressible gas of this analogy has a ratio of specific heat of 2.0 as compared to 1.4 for air. The quantitative effect of this can be seen in figures 7 and 8. If the cross sectional shape of the water channel is altered from the rectangular shape, the value of the specific heat ratio is changed (ref 4). This could be of concern if one were interested in transmission lines, etc.

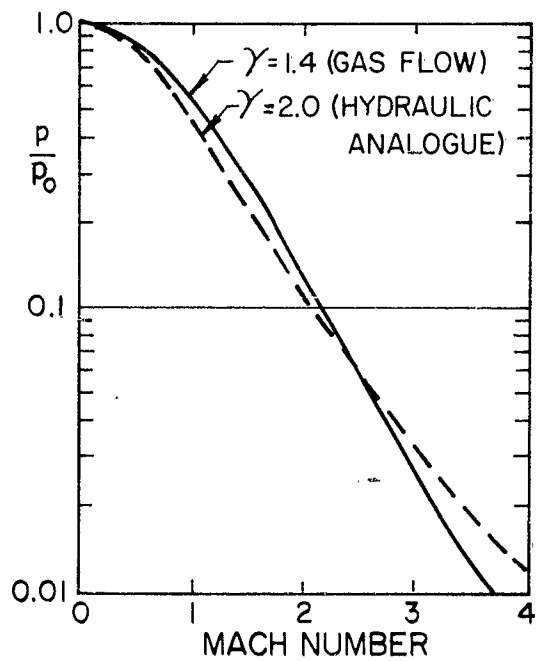


Figure 8. Pressure ratio versus Mach number for isentropic flow. Effect of specific-heat ratio. (Credit A. H. Shapiro)

3.2.7 Conclusion

Abstracts on the theory and application of the hydraulic analogy are given in Appendix A and the original reports should be consulted for specific details on parameters discussed in this section. The various shortcomings of the analogy that have been discussed should be considered in designing experiments and drawing conclusions.

In spite of its limitations, the hydraulic analogy gives an excellent return in terms of qualitative appraisals, design comparisons, flow visualization, and generation of new concepts in the field of fluid-interaction devices. No fluid-interaction program should be without a water table.

4. EXPERIMENTS USING THE HYDRAULIC ANALOGY

4.1 Water Table

Two water tables were used for the investigation of the fluid interaction devices described herein. One table was constructed at HDL; the second was operated under a contract with the University of Maryland. The design characteristics of both tables are in general similar.

In the table at HDL the water is pumped from a settling basin by centrifugal pumps of various sizes directly to reservoirs on the flow surface. After flowing through the test models, the water returns to the settling basin prior to recirculation through the pumps.

The flow surface used in most tests is a 3/8-in. thick sheet of plate glass. The height and inclination of the sheet can be adjusted to provide various test conditions. Adjustable lamps are installed under a second glass plate beneath the flow surface to illuminate the tests. This light is diffused with a sheet of translucent plastic having a grid marked on it for ease of setting up tests and plotting flow paths. This is shown most clearly in figure C1, Appendix C.

4.2 Performance of a Subsonic Diffuser

This section concerns the first semiquantitative experiment at HDL using the hydraulic analogy. The experiment was conducted to determine the most effective diffuser for obtaining pressure recovery downstream from the power jet nozzle.

Pressure recovery, as generally used, means the process of converting the dynamic pressure of a fluid stream into static pressure. Pressure recovery is an important parameter when a fluid amplifier is made to operate into a load.

The pressure recovery coefficient is based on the equation (ref 5)

$$C_{PR} = \frac{P_2 - P_1}{q_1}$$

where

C_{PR} = pressure recovery coefficient

P_1 = static pressure at throat

P_2 = static pressure in the diffuser

q_1 = dynamic pressure in the throat.

Using the analog relation $p/p_o = (d/d_o)^2$ given in section 3.1

$$\frac{p_2}{p_o} - \frac{p_1}{p_o} = \left(\frac{d_r}{d_o}\right)^2 - \left(\frac{d_t}{d_o}\right)^2 \text{ , and } \frac{q_1}{p_o} = \left(\frac{d_r}{d_o}\right)^2 - \left(\frac{d_t}{d_o}\right)^2$$

It follows that

$$C_{PR} = \frac{d_r^{\,2} - d_t^{\,2}}{d_o^{\,2} - d_t^{\,2}}$$

where

p_o = stagnation pressure in reservoir

d_r = depth in diffuser

d_t = depth in throat

d_o = depth in reservoir

4.2.1 Equipment and Procedure

Figure 9 shows the shape of the hydraulic models used. The fluid entered through a nozzle of width w, and depth measurements were obtained from probe readings of the bottom and the surface of the water.

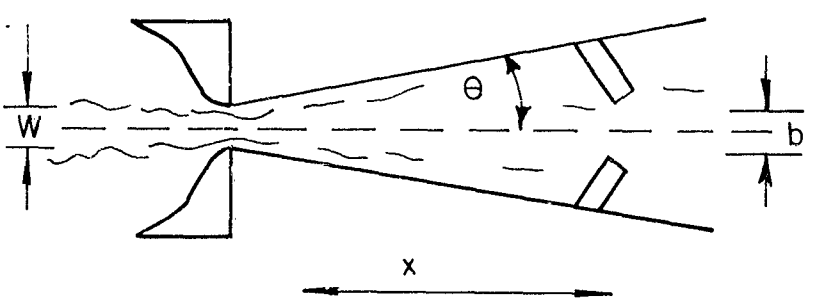


Figure 9. Simple diffuser directly downstream from nozzle.

Preliminary tests were made of diffusers with a large total included angle 2θ. For large-angle diffusers, the jet tended to confine itself to a narrow stream, usually along a diffuser wall, with the resultant generation of large eddies and often of backward-directed streams. With reduction of the diffuser angle, the eddies reduced in size and the backward current ceased. For diffuser angles 2θ up to 8 deg, the jet filled most of the diffuser, and, while decelerating, it divided into many small eddies.

Depth readings were taken along the axis for different flow rates and for several values of the exit opening b. Both of these

Table I. Percentage of Dynamic Pressure at Nozzle Throat Recovered in 4-deg Subsonic Diffuser

	Test A	Test B	Test C	Test D
Upstream reservoir water depth (d_o), in.	0.538	0.532	0.506	0.538
Water depth in nozzle throat (d_t), in.	0.520	0.473	0.349	0.429
Maximum water depth recovered in diffuser (d_r), in.	0.530	0.508	0.435	0.486
Mach number in throat	0.263	0.385	0.90	0.695
Percentage of (dynamic pressure) recovered	55.3	58.0	50.2	49.5

variables affect the flow through the diffusers by influencing the upstream and diffuser water depths.

4.2.2 Discussion of Results

Depths measured along the centerline of 4-deg diffusers, ($2\theta = 4$ deg) are presented in figures 10, 11, 12, and 13. Each graph is similar in that the water depth is a minimum at the nozzle throat after which it builds up again in the diffuser. The static pressure recovery reaches a maximum at a point approximately 25 w downstream.

The water depth measurements were used to calculate the Mach number and percentage of dynamic pressure recovered. The measurements used in the calculation and results are presented in Table I. Average pressure recovery was 53.2 percent for the four tests.

The average pressure recovery for a 5.37-deg diffuser with the air terminating in an open reservoir was 79.6 percent (ref 5). Roughly, then, the pressure recovery in a water table is about 67 percent as efficient as the pressure recovery with air. This can be partially attributed to the unbalanced drag on the water; i.e., no drag on the free surface compared to the drag of the bottom.

4.2.3 Conclusion

This simple experiment was selected as suitable for acquiring experience in the operation of a water table. The similari-

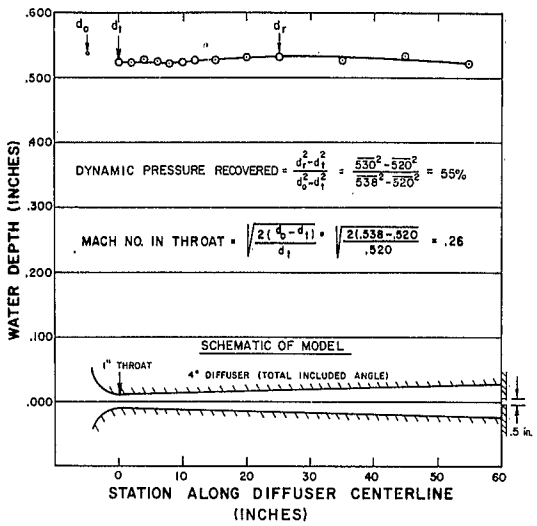


Figure 10. Test A—centerline water depth in a 4-deg diffuser with a 1/2-w wide exit 60 w downstream.

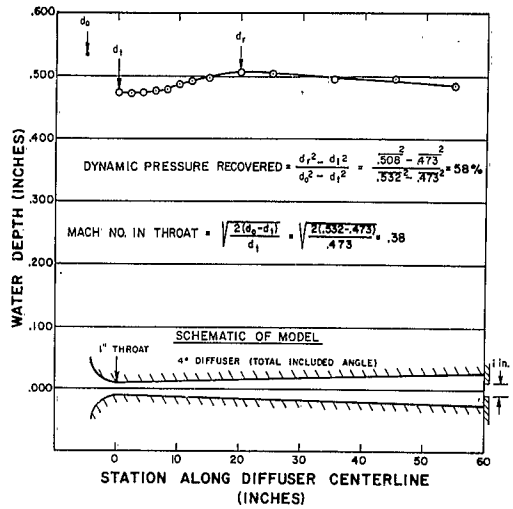


Figure 11. Test B—centerline water depth in a 4-deg diffuser with 1-w wide exit 60 downstream.

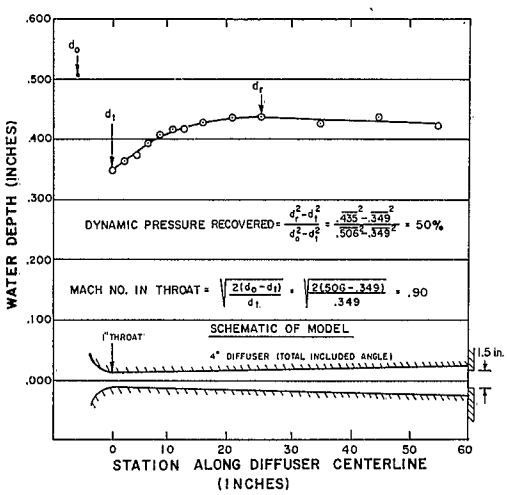


Figure 12. Test C—centerline water depth in a 4-deg diffuser with 1.5-w wide exit 60 w downstream.

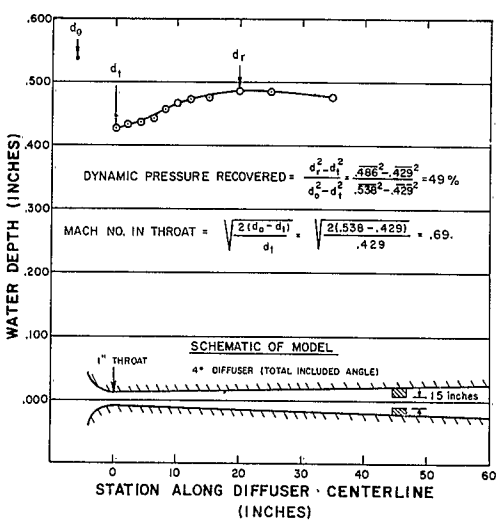


Figure 13. Test D—centerline water depth in a 4-deg diffuser with a 1.5-w wide exit 45 w downstream.

ties and differences in behavior of hydraulic and gaseous diffusers were of interest. In particular, it was noted that the water model of a subsonic diffuser is considerably less efficient than the corresponding compressible gas diffuser.

4.3 Performance of a Three-Stage, Closed-System Bistable Fluid Amplifier

The operation of bistable fluid amplifiers in a closed system cascade is very much more complicated than the operation of a single amplifier. This complication arises from the interaction of one fluid amplifier upon another where no dumping between stages is permitted. The water table is a very useful tool in investigating cascaded systems.

4.3.1 System Description

The system is shown in figures 14 and 15. A requirement is that the power-jet pressure of all three stages be the same, since it was felt that in a practical design, a common power supply would be desirable. The common power supply was produced on the water table by cutting holes in a sheet of plastic that formed the flow surface and by flooding the volume beneath with water at the desired pressure. The power jets have the following approximate widths: first stage - 0.025 in., second stage - 0.625 in., third stage - 4 in.

The output flow from the first stage passes through a crude diffuser and becomes the control flow for the second stage. All of the flow is retained. The unused output from the first stage to the second stage is of course open and provides a feedback path that complicates the system. The second stage output provides the control flow for the third stage with a similar feedback path.

The input signal to the first stage is provided by pumping water through a small plastic hose into one or the other of the first-stage control reservoirs. The resulting control flow causes the first-stage output to be switched into the output on the opposite side. The first-stage output switches the second stage, which switches the third stage. The third-stage output flows directly to a downstream reservoir through the proper exit passage.

The small circles in figure 14 indicate where readings of static pressure and total pressure were taken. The readings were taken at the center of each circle. The radial line inside each circle indicates the direction (center to circumference) in which the underwater pitot tube was pointed to obtain the measurements. The water pressures were read on a water-air manometer with the aid of 20x magnification (Appendix E).

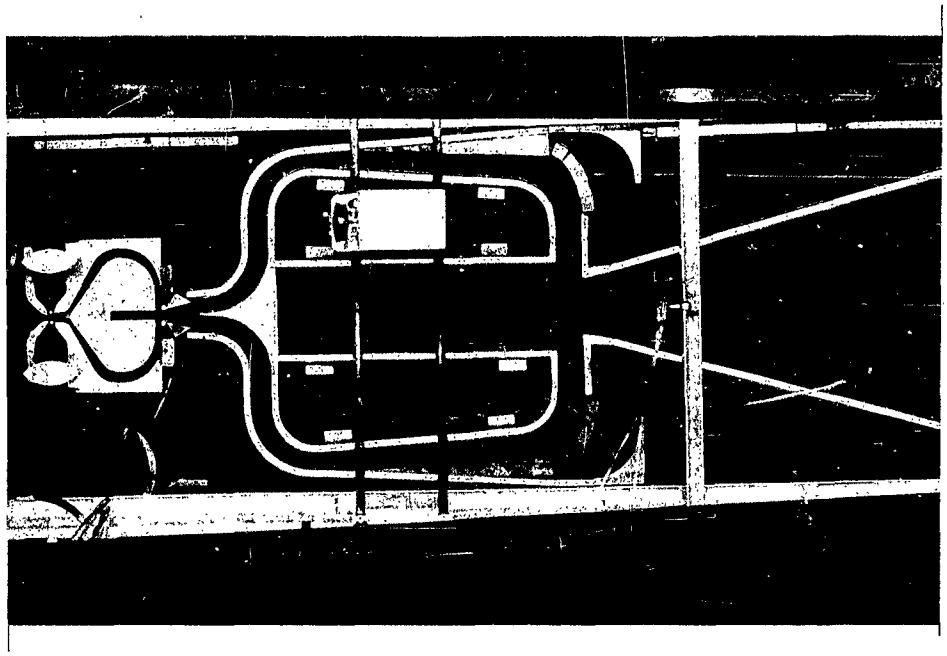


Figure 14. Three-stage water-table model.

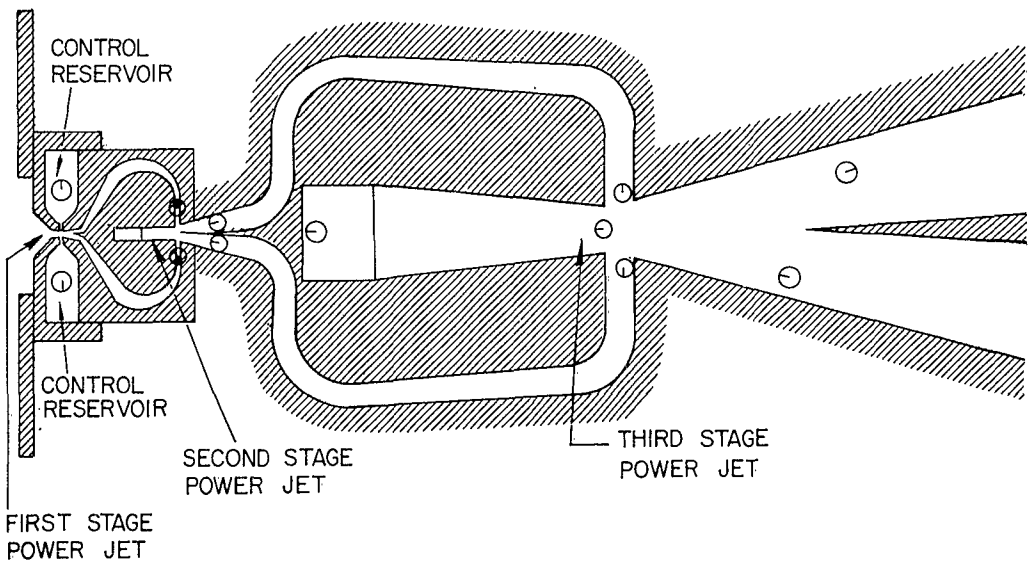


Figure 15. Schematic of three-stage water table model . Water is supplied to the three power jets by means of holes in the plastic flow sheet.

4.3.2 Results

The results obtained from the hydraulic tests of the three-stage model are given in figure 16. The overall pressure ratio is the downstream pressure into which the third stage exhausts divided by the first-stage power-jet pressure. All pressures are the corresponding compressible analog-gas pressures computed from measurements of the water depth at the appropriate points on the water table.

The third row gives the power-jet pressure (psig) that one obtains using the overall pressure ratio and the assumption that the downstream ambient pressure is atmospheric (14.7 psia).

In the column just to the right of the photograph of the model, the word "flow" appears five times. This is to indicate that the signal flow and the principal flow through the model existed at the various measuring points labeled with the word "flow."

The bulk of the table is given to listing the total and static pressure of the analog gas. These pressures are in psig. Where there is no velocity, the total pressure is the same as the static pressure, as is seen for the control reservoir in all tests. For example, in test A, the total and static pressures are listed as 1.49 psig. On the other hand, data from the flow-side of the third-stage output yields a total pressure of 1.86 psig and a static pressure of 0 psig.

4.3.3 Discussion

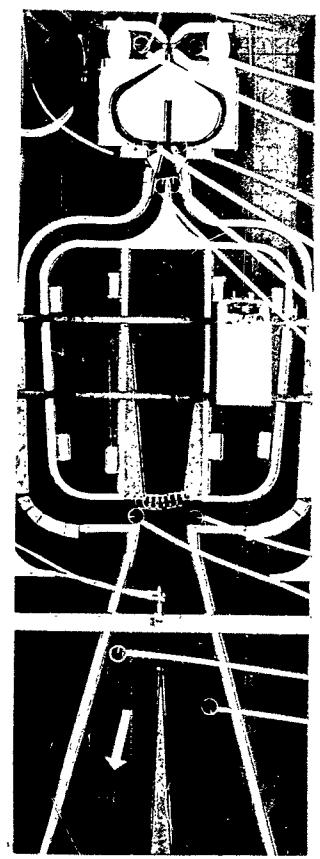
While the use of a three-stage model does provide the experimenter with an interesting system to observe, it becomes rather difficult to isolate variables and discover what is fundamental to staged operation. The configuration of each stage plays an important part, and many configurations are possible.

4.3.4 Conclusion

Closed-system, three-stage operation of a bistable fluid amplifier can be observed on the water table. Measurements can be made easily. The system will operate under quite a large range of pressures and will tolerate considerable variation of geometry. However, single stages under an assortment of loads should be thoroughly investigated as a prelude to three-stage studies.

4.4 Switching of Bistable Amplifiers

A control stream switches the course of the power stream primarily by causing the static pressure on one side of the power stream to be greater than on the other; however, momentum exchange also has some effect. The designer has many choices to make regarding



Test	A		B		C		D		E	
Overall Pressure Ratio (p_a/p_o)	.83		.807		.653		.585		.392	
p_o in psig based on p_a at atm.	2.98		3.5		7.8		10.4		37.5	
	p_t	p_s	p_t	p_s	p_t	p_s	p_t	p_s	p_t	p_s
					(psig)					
flow	1.49	1.49	1.57	1.57	3.01	3.01	5.54	5.54	34.76	34.76
——	1.32	1.32	1.37	1.37	2.57	2.57	4.92	4.92	25.10	25.11
——	1.42	1.39	2.08	1.94	4.41	4.18	5.88	5.97	25.11	25.88
flow	2.06	1.76		.74	5.43	4.56	7.05	6.56	28.97	26.37
flow	1.66	1.29	1.84	1.27	4.07	2.68	7.10	5.59	26.51	18.62
——	.64	.45	.71	.81	2.47	2.08	3.40	3.81	17.94	16.62
flow	1.19	1.06	1.34	1.54	3.15	2.86	3.17	2.68	28.31	18.51
——	.61	.54	.61	.58	2.65	2.33	2.11	1.29	16.77	16.38
flow	1.86	0	1.50	0	4.03	0	6.71	.29	18.82	0
——	.06	.10	2.42	0	.40	.40	.25	0	4.79	4.69

Figure 16. Data Sheet - three-stage model.

the configuration of the interaction region and the relative size of the control openings. An experiment was conducted to determine the role of the control opening size and control fluid velocity in switching fluid amplifiers.

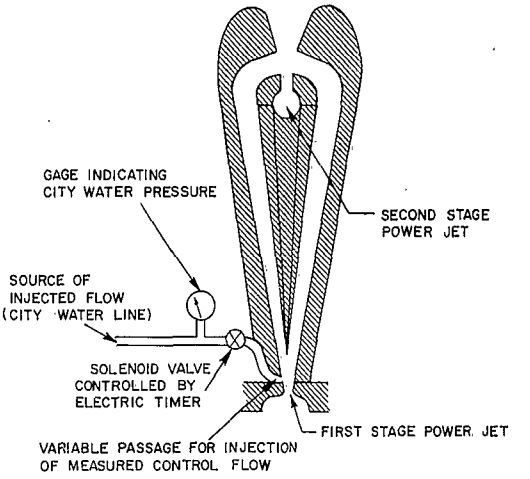


Figure 17. Bistable element.

4.4.1 Apparatus

Figure 17 shows a schematic diagram of the apparatus. Essentially, the apparatus is a variable control opening attached to a water-table model of a bistable fluid amplifier. An electric timer and a solenoid-actuated valve provide a controlled fluid injection time. Measurement of the volume flow permits calculation of the average velocity of the injected flow.

4.4.2 Results

Figure 18 shows the kinetic power needed to switch with a 30-sec injection for various sizes of control opening.

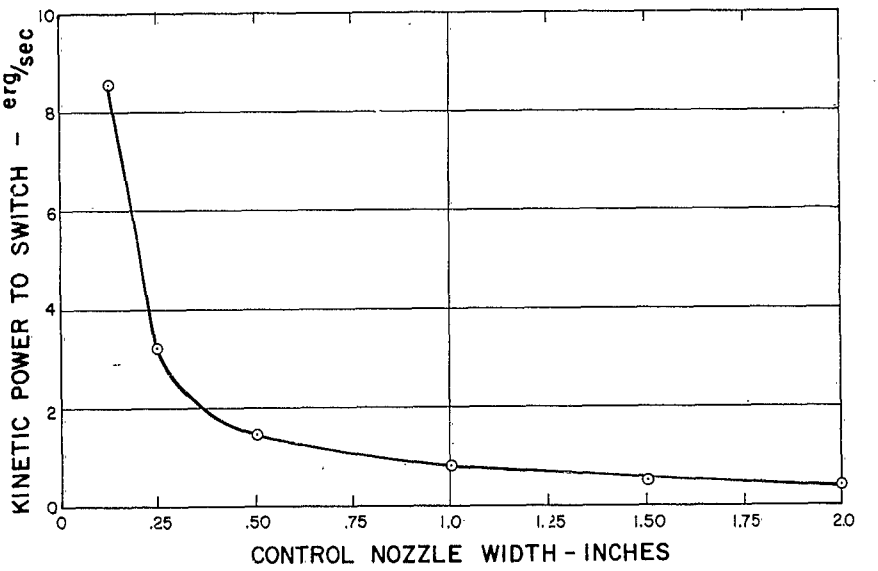


Figure 18. Kinetic power (30-sec pulse) needed to switch as a function of control nozzle width.

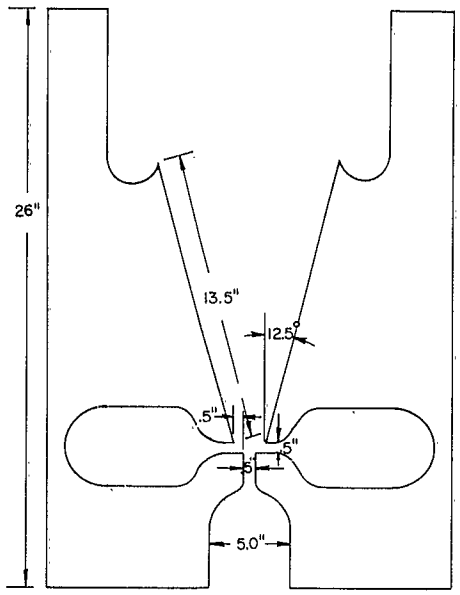


Figure 19. Final model

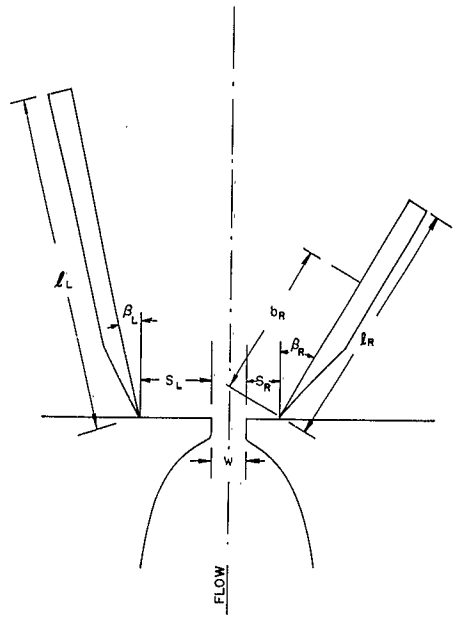


Figure 20. Adjustable model

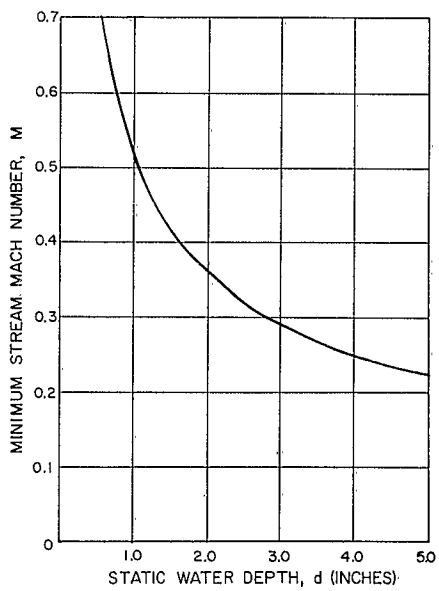


Figure 21. Minimum stream Mach number at which capillary waves form.

4.4.3 Conclusion

The experiment is included here mainly to suggest the kinds of experiments that can be satisfactorily performed on the water table. The data suggests that bistable units can be switched with very little kinetic power. In this type of switching, the control flow fills up the low-pressure attachment bubble and detaches the stream from the wall.

4.5 Effect of Design Parameters on Stream-Attachment Characteristics

The water table at the University of Maryland Aeronautical Laboratory that was used for this investigation is 22 ft long and 30 in. wide. The water was pumped into a 30-in. wide stagnation region from which it flowed with gradual narrowing to a 5-in. wide channel preceding the 0.5-in. wide nozzle throat. The water depth readings were obtained at the stagnation region and at the nozzle exit with probes to determine the Mach numbers at the nozzle exit.

Two models were tested, a fixed model and an adjustable model. The fixed model (fig. 19) has a setback (S_L and S_R) fixed at 0.5 in. on both sides, and diffuser angles (β_L and β_R) of 12.5 deg., also on both sides. The adjustable model (fig. 20) differs in that the setback, the diffuser angles, and the wall length (ℓ_L and ℓ_R), and the nozzle width w can be varied independently.

In most tests with both models, simulated Mach numbers of 0.5 and 1.2 were used. For the Mach-0.5 tests, a depth of approximately one inch was chosen as the value at which the flow is most stable and at which interference of capillary waves is a minimum. Figure 21 shows the relation of Mach number and stagnation depth at which there is a minimum of disturbing capillary waves, for the subsonic range. In the supersonic range, the analogy of water-table flow to two-dimensional gas flow exists only for a water depth of approximately 0.25 in. (ref 4).

4.5.1 Procedure

Fixed Model—The fixed model was set up as shown in figure 22 with the solid splitter moved along the center line. For Mach numbers 0.5 and 1.2, the splitter was set at selected positions downstream from the nozzle. The flow patterns were recorded on 16-mm color film. Moving pictures were taken for each of the following conditions: (1) undisturbed flow; (2) the left output channel was blocked; (3) the right output channel was blocked. The point of flow attachment was determined for undisturbed flow and with the left channel blocked; and it was determined whether the flow switched if the right output channel was blocked. Similar procedures were followed with the unit having the divided splitter (fig. 23). The splitters were moved up and down stream and also laterally to give various combinations of side channel and midchannel widths.

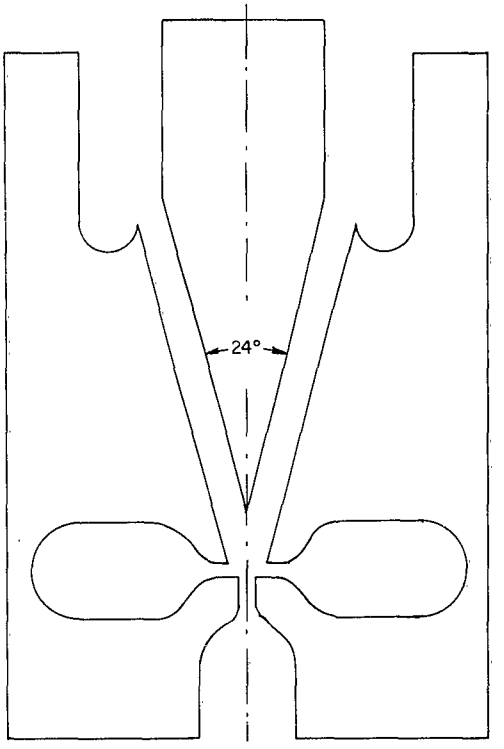


Figure 22. Fixed model with solid splitter.

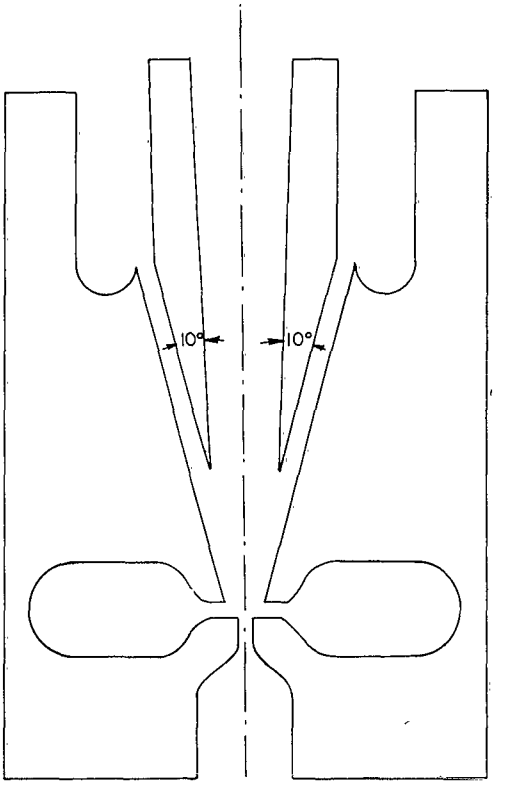


Figure 23. Fixed model with divided splitter.

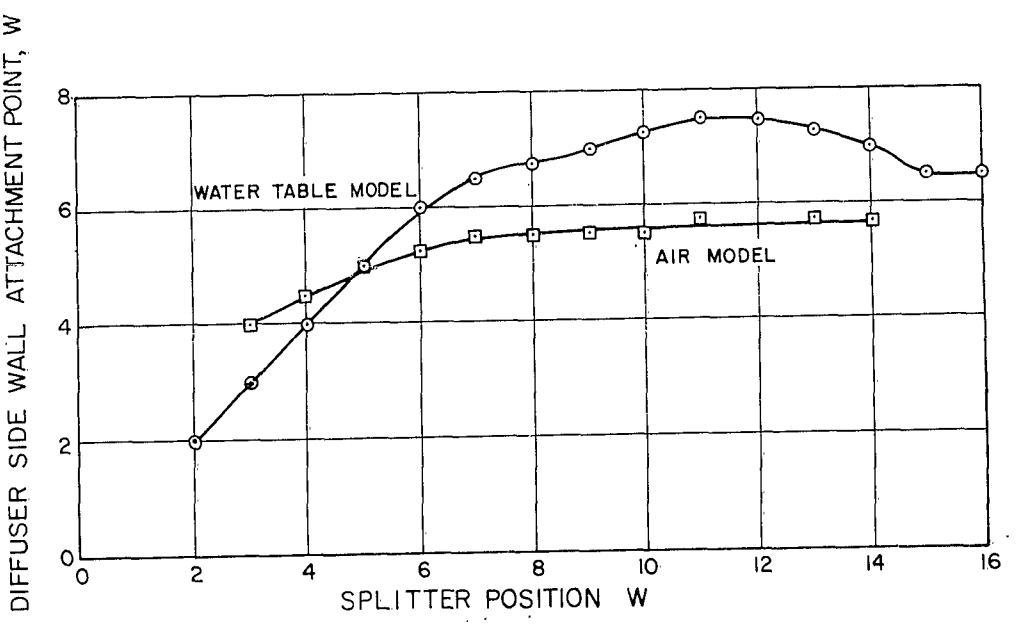


Figure 24. Diffuser side-wall attachment point.

Adjustable Model—The adjustable model (fig. 20) was used to investigate the effect of configuration changes on flow characteristics. A blue dye was introduced through a tube placed in the flow near the diffuser wall, and the tube was moved parallel to the wall by a motor. The point of attachment was determined by observing the position of stagnation along the wall.

In the tests, the right side wall was set at some angle β_R. After flow stabilization, the point of attachment was determined. This procedure was followed until angle β_R became sufficiently large for the contact point to break away, allowing the stream either to follow the center of the channel or to attach to the opposite wall. The angle β_R was then reduced to a value such that the flow reattached to the right wall. In some cases, β_R must become negative, and in others, the flow simply does not return to the right hand wall.

4.5.2 Results and Conclusions

A series of motion pictures showing the flow-pattern variations with changes of splitter distance downstream from the nozzle, channel widths, and side-wall angles, vividly demonstrates the flow behavior in the fluid amplifier channels. The phenomena of wall-attachment behavior when the outlet channels are blocked are clearly shown in slow motion as compared to the gaseous-flow analogy.

Figure 24 presents results from a part of the motion pictures taken with the fixed model, and in addition, data from an analogous investigation of a two-dimensional gaseous model. For both water and air, the diffuser wall attachment distances from the nozzle (in units of nozzle width w) are plotted against the distances of the splitter from the nozzle (also in units of nozzle width). For the water-table curve, the values of attachment distance were essentially independent of velocity over a simulated velocity range of Mach numbers from 0.2 to 0.6. For the air diffuser experiment, a similar negligible variation of attachment distance with velocity was observed.

Acknowledgments

David S. Marsh and James D. Beardsley also participated in this study.

5. REFERENCES

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(3) Hoyt, J. W., "The Hydraulic Analogy for Compressible Gas Flow," Appl. Mech. Rev., Vol 15, No. 6, June 1962, pp 419-425.

(4) Shapiro, A. H., "An Appraisal of the Hydraulic Analogue to Gas Dynamics," Meteor Report No. 34, Massachusetts Institute of Technology, April 1949.

(5) Reid, E. G., "Performance Characteristics of Plane-Wall Two-Dimensional Diffusers," NACA Technical Note 2888.

(6) Ibid., p 17.

APPENDIX A. ABSTRACTS ON THE THEORY AND APPLICATION OF THE HYDRAULIC ANALOGY

AN APPRAISAL OF THE HYDRAULIC ANALOGUE TO GAS DYNAMICS

Shapiro, A. H., Meteor Report No. 34, Massachusetts Institute of Technology, April 1949.
The assumptions of the hydraulic analogue to gas dynamics are reviewed in the light of recent experience, with the aim of assessing the analogue as a practical tool. Some experimental techniques are discussed, and some typical results obtained with a "supersonic water channel" are presented. It is concluded that the water channel is a valuable instrument for making qualitative studies and for making quantitative studies of a comparative nature but does not lend itself to obtaining direct design data.

STUDIES ON THE VALIDITY OF THE HYDRAULIC ANALOGY TO SUPERSONIC FLOW

Harleman, D. R. F. and Boedtker, O. A., Air Force Technical Report No. 5985, Wright-Patterson Air Force Base, May 1950 (revised January 1951). (Reviewed by Dr. J. G. Moorhead.)
Part I—Abstracts are given of nine reports found to be most pertinent during a careful study of previous research on water tables. A water table was designed and constructed. Measuring techniques were systematized, and the instruments required were calibrated.
Part II—After developing the equations of hydrodynamics pertinent to the water table, the equations for gas dynamics and analogies existing for the two types of flow, two modifications to the usual procedures are derived for using the analogy. In Modification I, the depth ratios at points on the water table are used to give the analogous pressure ratios in the gas. The gas equations are then used to determine the various quantities existing in the gas. Modification II for flow involving shocks adjusts the shock angles in gas and water with resultant changes in the Froude and Mach numbers, and the density ratios. The new density ratios are incorporated into Modification I for determination of the gas quantities. When the modifications were employed in computing experimental data, satisfactory comparison of results for water and for gas flows was obtained.

WATER TABLE EXPERIMENTS ON TRANSIENT SHOCK-WAVE DIFFRACTION, PART II—EXPERIMENTAL RESULTS AND EVALUATION, OCTOBER 1954

Harleman, D. R. F., Boedtker, O. A. and Wolf, S., Contract AF(616)-107 Wright-Patterson Air Force Base, October 1954. (Abstract by Dr. J. G. Moorhead.)
An investigation was conducted of the pressure distributions and drag forces caused by transient diffraction of shocks around bodies of simple geometrical configuration in the shock tube and on the water table. The equations relating wave velocities and depth ratios for incident and

reflected shock waves on the water table were developed along with the analogous equations pertaining to shock waves in gases. Computation techniques were developed and graphs were prepared for correlating depth ratios and Froude numbers of water waves with pressure (or density) ratios and Mach numbers of gas waves. A reservoir shock-wave generator was constructed for the water table. A capacitance type depth instrumentation was developed. The addition of 1% sorbitan monolaurate to tap water was found to decrease surface tension errors in the depth measurements.

An extensive series of tests was conducted of the incident and reflected water waves with various interfering obstacles. Computations were graphed along with computations of analogous quantities from corresponding experiments on shock tubes. For simple geometrical models used as obstacles with which multiple-reflection shock waves are not present, the water table results are quantitatively comparable, within about ten percent, to shock tube results. For more complex models the water table results are less satisfactory other than for peak pressures. The water table method is generally not satisfactory for detailed studies of small pressure changes due to local variations in the model geometry. It is concluded that the water table can best serve in making exploratory tests before conducting more detailed experiments with the shock tube.

STEREOPHOTOGRAMMETRY APPLIED TO HYDRAULIC ANALOGUE STUDIES OF UNSTEADY GAS FLOW

Mann, R. W., Report No. 8543-1, Department of Mechanical Engineering, Massachusetts Institute of Technology, March 30, 1962. (Abstract by Dr. J. G. Moorhead)

Equipment was set up to obtain by stereophotogrammetry the time-varying elevations of points on the surface of a water table. The particular model under investigation was the analogy to the unsteady two-dimensional compressible gas flow through a partial-admission turbine. The basic theory is discussed and the experimental procedure is described. The measurements of pressures in the flow region were sufficiently accurate to be compatible with water table accuracy and increased accuracy could be obtained if desired.

APPLICATION OF THE METHODS OF GAS DYNAMICS TO WATER FLOWS WITH FREE SURFACE, PART I—FLOWS WITH NO ENERGY DISSIPATION; PART II—FLOWS WITH MOMENTUM DISCONTINUITIES (HYDRAULIC JUMPS)

Preiswerk, Ernst, NACA Technical Memos 934 and 935, 1940. (Abstract by Dr. J. G. Moorhead.

The equations of gas flow, free surface liquid flow, and the analogies between these two flows are developed. Then there is given a very comprehensive development of the method of characteristics.

APPLICATION OF THE ANALOGY BETWEEN WATER FLOW WITH A FREE SURFACE AND TWO-DIMENSIONAL COMPRESSIBLE GAS FLOW

Orlin, W. J., Lindner, N. J., and Bitterly, J. G., NACA Technical Note 1185, August 21, 1946.
The theory of the hydraulic analogy, that is, the analogy between water flow with a free surface and two-dimensional compressible gas flow, and the limitations and conditions of the analogy are discussed. A test was run using the hydraulic analogy as applied to the flow about circular cylinders of various diameters at subsonic velocities extending into the supercritical range. The apparatus and techniques used in this application are described and criticized. Reasonably satisfactory agreement of pressure distributions and flow fields existed between water and air flow about corresponding bodies. This agreement indicated the possibility of extending experimental compressibility research by new methods.

AIR-WATER ANALOGY AND THE STUDY OF HYDRAULIC MODELS

Supino, Giulio, NACA Technical Memo 1359
The author first sets forth some observations about the theory of models. Then he established certain general criteria for the construction of dynamically similar models in water and in air, through reference to the perfect fluid equations and to the ones pertaining to viscous flow. In addition, it is pointed out that there are more cases in which the analogy is possible than is commonly supposed.

THE DESIGN, OPERATION, AND USES OF THE WATER CHANNEL AS AN INSTRUMENT FOR THE INVESTIGATION OF COMPRESSIBLE-FLOW PHENOMENA

Matthews, C. W., NACA Technical Note 2008, January 1950.
Attempts to use the 20-in-wide water channel at the Langley Laboratory for research projects led to difficulty in the interpretation of the data with respect to practical flight problems because of the low value of the Reynolds number in the water channel. A channel permitting Reynolds numbers as large as 3,000,000 at tunnel choking would have to be approximately 10 feet wide if the water temperature were 200°F or 20 feet wide if the water temperature were 100°F.
The problem of maintaining a stable stream velocity has been solved by using a weir to control the total head and a variable-width Laval nozzle to control the mass flow through the channel. This system was capable of holding the stream velocity constant within one-half of 1 percent for an indefinite period.
The water channel is recommended as an effective low-cost demonstration instrument for use in the teaching of aerodynamic compressible flow and as an instrument for quickly checking new ideas.

PERFORMANCE CHARACTERISTICS OF PLANE-WALL TWO-DIMENSIONAL DIFFUSERS

Reid, E. G., NACA Technical Note 2888. (Abstract by Dr. J. G. Moorhead)
The earlier investigations of diffusers are very comprehensively reviewed. The test program herein discussed was intended to extend the range of earlier experiments in such a way as to correlate such quantities as pressure recover, pressure efficiency, and volumetric efficiency with the parameters length and divergence angle. The investigations included tests with asymmetric diffusers, exit ducts, and longitudinal partitions.

A STUDY OF DETACHED SHOCK WAVES BY THE WATER CHANNEL-COMPRESSIBLE GAS ANALOGY

Hedgecock, J. L., Graduate Division of the University of California, 1948.
The analogy between two-dimensional gas flow and water flow with a free surface was used in conjunction with the shadowgraph method of photography to obtain data on the location of a detached shock wave with respect to several wedge models at various Mach numbers. The data are compared with a theory developed by Prof. E. V. Laitone of the University of California. The agreement between theory and experiment is seen to be best for the smallest wedge angle tested with the deviation varying with the size of the wedge angle.
A water table was built and techniques were developed for photographing the waves ahead of a wedge while being towed at constant velocity in still water.

THE DEVELOPMENT OF EXPERIMENTAL TECHNIQUES FOR THE STUDY OF COMPRESSIBLE FLOW BY THE HYDRAULIC ANALOGY

Flowers, J. Val, University of California, 1948.
The optimum experimental conditions were re-examined for obtaining water tank flows analogous to two-dimensional compressible flow. Water depth, surface tension, and model size were varied to determine their influence on the "transonic" flow about wedges and cylinders in shallow water. A study was also made of the detachment of the shock wave as a function of the Mach number for cylinders in transonic flow.
Pure water at a depth of .25 inch yielded optimum results. Reducing the surface tension of the water had an adverse effect on the transonic flow at this depth. Model size was found to be of secondary importance. The data obtained for the shock detachment for circular cylinders are compared with several approximate theories for predicting shock location.

A STUDY OF TRANSONIC GAS DYNAMICS BY THE HYDRAULIC ANALOGY

Laitone, E. V., Jour.of Aero. Sci., Vol 19, No. 4, April 1952.
The theory governing the propagation of surface water waves is analyzed to show that an analogy with the two-dimensional flow of a perfect gas exists only if the water depth is approximately 1/4 in., the model is fairly large, and the shock waves or hydraulic jumps present are of the weak type having a negligible increase in entropy.

Photographs of the water surface waves corresponding to shock waves in front of simple wedges and circular cylinders are presented to illustrate these restrictions. It is pointed out that the surface-wave group velocity, which could be considerably less than the so-called wave velocity, provided the only correct analogy to the speed of sound in two-dimensional gas flow over a closed body.
Motion pictures were taken in order to study the effect of constant acceleration on bow shock waves. It was found that at high rates of acceleration the location of the detached shock wave was dependent mainly on a nondimensional acceleration parameter and was practically independent of the instantaneous Mach number.

MACH REFLECTIONS IN TWO-DIMENSIONAL DIFFUSERS FROM HYDRAULIC ANALOGY EXPERIMENTS

Laitone, E. V. and Stout, J. E., Jet Propulsion, p 257, April 1958.
The separation distance required to prevent the formation of a Mach reflection between two wedges, representing either a two-dimensional diffuser or a Busemann biplane, is obtained by assuming that the normal shock wave could not have been created if the first expansion wave from the shoulder of the wedge would intersect it. This hypothesis is verified experimentally for the special case corresponding to a specific heat ratio of $\gamma = 2$ by means of the shallow water hydraulic analogy.

INVESTIGATION OF THE NATURE OF SURFACE RESISTANCE OF WATER AND OF STREAM-LINE MOTION UNDER CERTAIN EXPERIMENTAL CONDITIONS

Hele-Shaw, H. S., Nature (London) May 12, 1898. (Abstract by Dr. J. G. Moorhead.)
Techniques are developed which make visible the flow along various surfaces and through channels of various geometries, such as the converging-diverging and the diverging-converging types. One method of making flow visible is the introduction of air bubbles. In general, better results were obtained by introducing streams of dye into the flowing water. The most successful dye used was a mixture of pyrogallic acid and iron sulphate.

APPLICATION OF THE WATER CHANNEL-COMPRESSIBLE GAS ANALOGY

Bruman, J. R., North American Aviation Inc., Report Na-47-87, 3 March 1947. (Abstract by Dr.J. G. Moorhead.)
This report includes a discussion of the flow of water in a free-surface channel with analogous relations to the flow of a compressible gas. The major part covers the design and construction of the tank and auxiliary equipment, particularly including a number of arrangements of lights and mirrors for use in photographic recording of flow phenomena.

FLOW VISUALIZATION

Lippish, A. M., Aeronautical Engineering Review, February 1958.
This paper is concerned with the development of techniques for photographing the flow patterns around bodies in air in the subsonic range.

The method followed employs streams of smoke emitted from a smoke rake. As an improvement over smoke produced by the burning of rotted wood, streams of fine oil mist are employed. When illuminated from behind the observer and viewed against a black background, streaks several feet long can be observed and photographed. By means of special lighting arrangement and high-speed photography patterns are obtained for the flow about various bodies.

TECHNIQUES OF FLOW VISUALIZATION USING WATER AS THE WORKING MEDIUM

Cutter, D. W., Smith, A. M. O., and Brazier, J. G., Douglas Aircraft Co., El Segundo Div., Report No. ES 29075, 15 April 1959
The techniques listed below were investigated as means of visualizing the flow on a water table. The report of the investigations serves as an operating manual in the use of the techniques employed.

1. Aluminum Powder, used on the surface or suspended throughout the liquid.
2. Electro-chemical-tellurium wire, hydrogen bubbles, and starch iodide.
3. Dyes--injected into the liquid or dissolving from quantities located in the flow.
4. Luminol--a fluid that becomes luminous when it reacts with another fluid.
5. Airbubbles produced at the fairing of a blunt body.
6. Gravity waves-surface analogs to the shock waves in supersonic airflow.

A STUDY OF JET DEFLECTION BY THE HYDRAULIC ANALOGY

Hoyt, J. W., Journal of Aerospace Sciences, p 752, June 1962
The water table is used to investigate the jet deflection from a converging-diverging nozzle cutoff at an angle to the axis. The flow in the nozzle and the discharge section is determined from shadowgraphs and momentum surveys. The experimental results on the water table are compared to results of tests with air.

THE FLOW UNDER GRAVITY OF AN INCOMPRESSIBLE AND INVISCID FLUID THROUGH A CONSTRICTION IN A HORIZONTAL CHANNEL

Proceedings of the Royal Society of London (A) 159, 899,592-608, April 1937
This paper is concerned with the flow of water under gravity in a horizontal channel with a Laval-type variation of cross-section, and the analogous flow of a compressible fluid. A theory of the water flow is considered which is precisely similar to that given by Reynolds for the flow of a compressible and inviscid gas through a nozzle. An experimental test was conducted which gave deviation from the theory for discharge and variation in depth of water along the axis of the channel. For thin sheets of water a hydraulic analogy to gas flow holds which approaches a series expansion solution given by Taylor.

THE HYDRAULIC ANALOGY FOR COMPRESSIBLE GAS FLOW

Hoyt, J. W., Appl. Mech., Rev., Vol 15, No. 6, 419-425, June 1962.
A history of investigations of the hydraulic analogy for compressible gas flow is given. A bibliography is included in which 126 references are listed.

APPENDIX B. DESIGN OF WATER TABLES FOR THE STUDY OF FLUID INTERACTION DEVICES

B1. TABLE

A sheet of glass or plastic may be used to provide a smooth horizontal surface over which the water flow is to take place. Glass is stiffer than plastic and probably a truer plane as commercially supplied. However, plastic is easier to machine and is not as subject to breakage.

The degree of planeness required has not been determined. Commercial plate glass seems to be quite acceptable, and it is difficult to improve on the planeness of the original glass. Extra supports may not be effective because of the stiffness of the plate glass. If the glass has a slight bow, it probably will not sag onto extra supports. Of course, thinner glass or a less-stiff material can be used with many supports but at the price of added complication, which would interfere with experimentation.

Water tables may use a single sheet of glass or two sheets. In tables with a single sheet, the glass plate holds the water and provides the flowing surface. Getting the glass horizontal may involve leveling the whole tank, but once done, there should be little need for readjustment. With a single plate, the table is easy to clean.

In tables with two sheets of glass, one holds the water and the other is merely supported in the water at the desired depth. The latter forms the flowing surface, bears no water load, and is easy to adjust. However, if dye is used in the table, the water between the two sheets may become dyed, which interferes with the illumination through the table and is difficult to clean.

B2. FLOW CONTROL

The main difference between water tables for fluid interaction work and other water tables is due to the flow requirements. Fluid interaction work is essentially the study of internal aerodynamics, where the flows required are relatively small and where flows in a number of different passages are of interest. Water tables have been used mostly for studies of external aerodynamics in which a relatively large uniform flow field is produced, and the flow around certain objects is observed. For external work, a single large pump is used effectively, whereas in fluid-interaction work, several small pumps are preferable.

Stilling chambers and flow straighteners are necessary but take a different form in fluid interaction studies. Large stilling and

straightening facilities are not required, since large flows are not used. Rubberized horse hair is an effective and versatile stilling material. Old automobile radiators may be cut up and used as flow straighteners.

Important requirements of the water table are adequate filling and draining facilities, since more of this is required than would be expected.

APPENDIX C. DESIGN AND FABRICATION OF HYDRAULIC MODELS

C1. DESIGN

In fluid interaction devices, one ribbon-like stream is deflected by another. If the interacting streams are much wider than they are deep, the results may be affected by the relatively large drag of the bottom. Therefore, the depth-to-width ratios of the streams (the aspect ratios) must be kept reasonable.

The size of the hydraulic models depends on whether the flow is to be subsonic or supersonic. For supersonic work, the water depth has to be 0.2 to 0.3 in. to give a wave velocity that is reasonably constant with variations in wavelength. This makes it difficult to obtain a reasonable aspect ratio with convenient model size. Models have been made, having stream widths of 0.2 to 0.9 in. at the interaction region. Hydraulic models of this size have been tested at HDL, and some of the phenomena of fluid interaction devices have been produced. However, no comparison has been made between the hydraulic phenomena obtained and phenomena that might be obtained with compressible gas.

In subsonic work, water depths of approximately 1 in. have been used, and model sizes have been designed to obtain interacting streams that are usually 1, 2, or 3 in. wide. Good stream deflection has been obtained with a stream 6-in. wide and 1-in. deep. Fluid interaction phenomena can be produced with the Reynolds number smaller by a factor of 100 than for an air analog. The effects of Reynolds number or Froude number have not been studied sufficiently at HDL to report further than this.

C2. FABRICATION

Water-table models of fluid-interaction devices are generally very easily assembled for the type studies previously described. The power-jet nozzle, which is a critical component, should be accurately machined from blocks of a suitable metal. The remainder of the model can often be formed by assembling bars, wedges, or strips of metal in the desired configuration. A set of brass, aluminum, or lead pieces in a variety of shapes can be used as basic building blocks to form many different configurations. Such blocks are particularly useful in helping the designer formulate and investigate new concepts. A good idea of the simplicity and flexibility of the water table model components may be obtained by studying figure C1 and C2. Figure C1 shows the first cusp-splitter flow-bleed amplifier designed for high pressure recovery. Figure C2 shows the original model made by B. M. Lorton of the two-stage fluid amplifier using a single power jet for both stages.

In addition to the use of metal as described above, other materials are suitable for noncritical parts, and have the advantage of being easier to fabricate. Models may be made from hardwood, sanded to very

acceptable accuracies, and finished by waterproofing with varnish or wax. Wooden molds can be used to cast models in plaster, plastics, or wax. This technique is particularly applicable to symmetrical models since right-hand and left-hand parts can be cast in the same mold with one piece being used in the inverted position. It may, of course, be necessary to anchor the light-weight components by weighting them down using lead blocks.

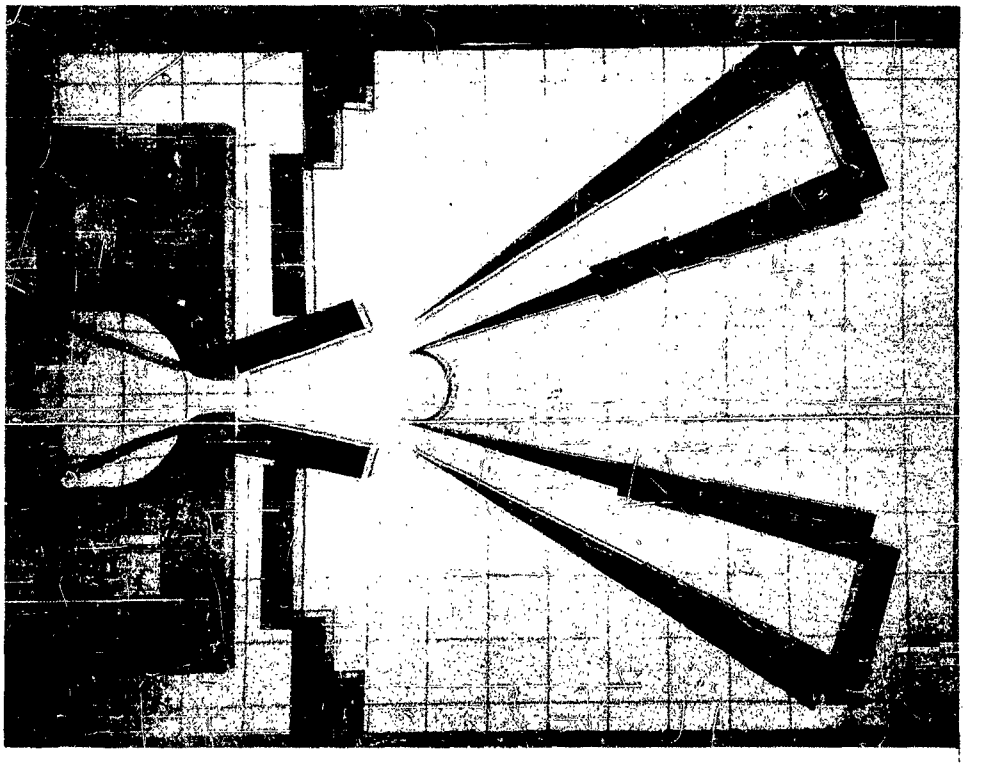

Figure C1. Bistable amplifier with cusp splitter, block load and flow bleed.

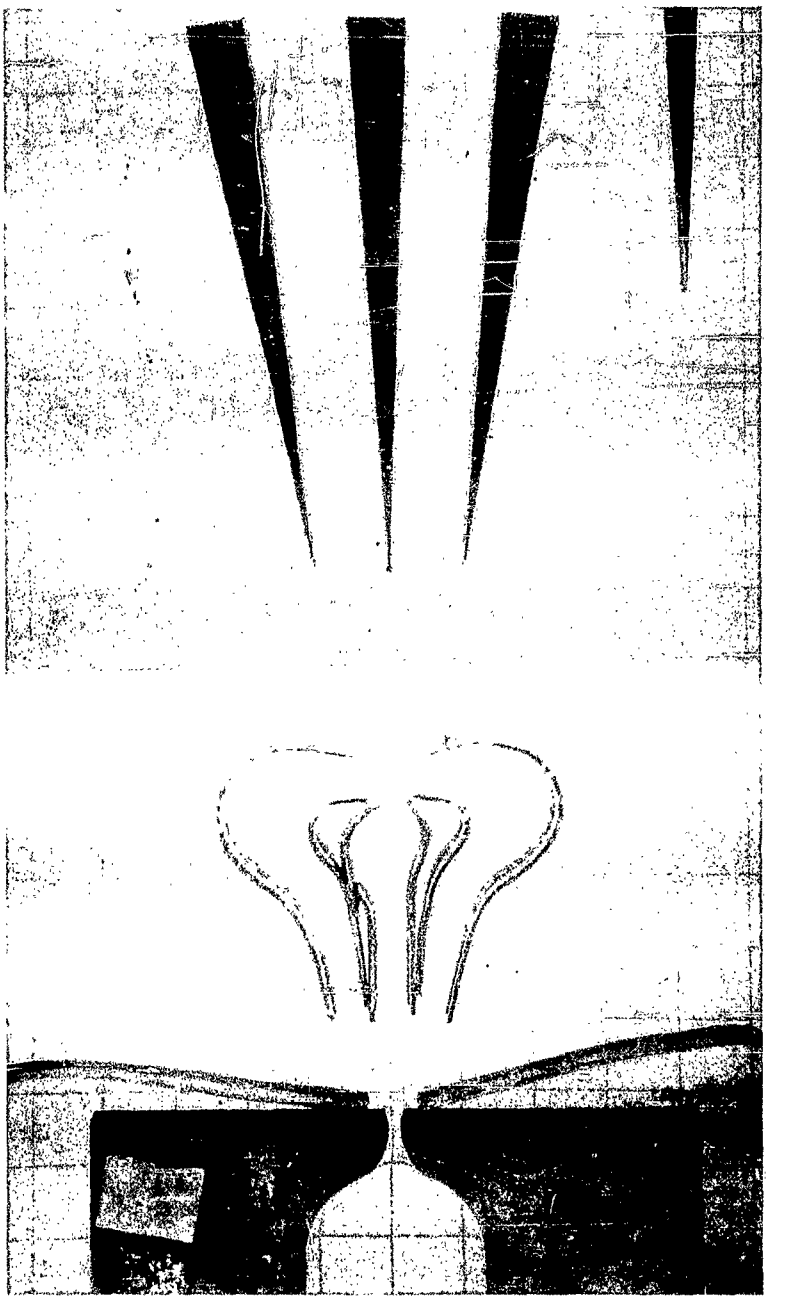

Figure C2. Two-stage fluid amplifier using only a single power jet (original water-table model).

APPENDIX D. FLOW VISUALIZATION

The flow pattern may, in general, be made visual by two methods--by adding a visible substance to the flow, or, by using a method dependent on the optical characteristics of the liquid.

D1. ADDITIVE FLOW INDICATORS

Dyes—Food and fabric dyes come in many colors. The fabric dyes are cheaper but the food dyes are easier to clean up. A red fabric dye called acid chrome blue is a good bright indicator. Photographic emulsion characteristics must be considered in choosing both the color and the intensity of the dye used.

Phenolphthalein—A basic solution of phenolphthalein gives a red color that disappears if the tank water is made slightly acid.

Solid Particles—Solid particles in the fluid or on the surface have been used as flow indicators. They have an advantage over dyes in that they keep their identity and do not diffuse away. Still pictures of solid particles may be taken with a slow shutter speed to obtain particle trajectories and a sense of fluid motion, and for making estimates of flow velocities. Aluminum flakes have been used (ref D1). At HDL, polyethylene pellets have been used. It is possible to make a neutral-density polyethylene pellet that should be better than the floating type for some applications.

Bubbles—Hydrogen bubbles produced in the flow by electrolysis have been used to indicate flow (ref D1). This technique is best where the liquid flow is deep and where external flow (flow around objects) is to be observed. The bubbles are not convenient for shallow flows, since the bubbles rise to the surface too soon, or with internal flows, since side illumination is required to obtain the best results.

D2. OPTICAL METHODS

Reflected Light—Waves can be observed by reflecting light from the water surface, but the resulting wave patterns are difficult to interpret.

Shadowgraph—Shadowgraphs have been used quite successfully in experiments (ref D2, D3, D4, D5). They are displaced from the waves producing them, however, and capillary waves, which are spurious, cause annoying shadows.

Schlieren—Schlieren techniques have possibilities. Inherently, schlieren techniques are more sensitive than is required, but it may be interesting to use schlieren pictures of hydraulic flow for comparison to existing schlieren pictures of analogous compressible gas flows.

Absorption Techniques—At HDL, heavily dyed water has been illuminated from below. The variation of absorption with depth makes waves and flows visible in supersonic flow (fig. D1). This technique minimizes the problem of interpretation and clearly shows the depth of the water as well as the wave patterns. The technique can be combined with shadowgraphs.

D3. REFERENCES

(D1) D. W. Clutter, A. M. O. Smith, and J. G. Brazier, "Techniques of Flow Visualization Using Water as the Working Medium," Report No. ES29075, Douglas Aircraft Co., El Segundo Div., 15 April 1959.

(D2) A. H. Shapiro, "An Appraisal of the Hydraulic Analogue to Gas Dynamics," Meteor Report No. 34, Massachusetts Institute of Technology, April 1949.

(D3) W. J. Orlin, N. J. Lindner, and J. G. Bitterly, "Application of the Analogy Between Water Flow with a Free Surface and Two-Dimensional Compressible Gas Flow," NACA Technical Note 1185, August 21, 1946.

(D4) E. V. Laitone, "A Study of Transonic Gas Dynamics by the Hydraulic Analogy," Jour. of Aero. Sci., Vol 19, No. 4, April 1951.

(D5) J. R. Bruman, "Application of the Water Channel-Compressible Gas Analogy," North American Aviation Inc., Report Na-47-87, 3 March 1947.

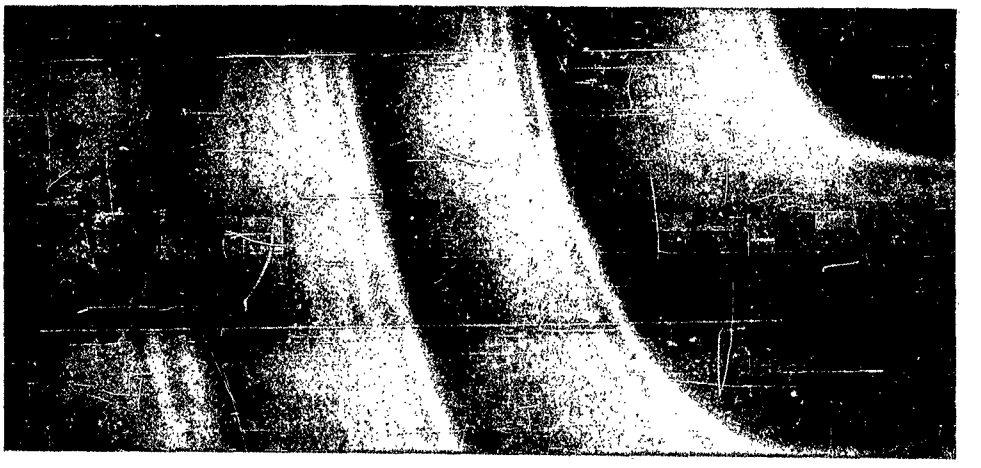

Figure D1. Water waves in dyed water.

APPENDIX E. INSTRUMENTATION

E1. PHOTOGRAPHIC EQUIPMENT

Photography is a convenient method of recording test data; e.g., the many geometrical shapes tested, the pattern of flow fields, position of pitot tubes, etc. Both still and motion picture photographs have their own special applications.

Cameras—At HDL, a 4 x 5 camera is used that accepts holders for roll and cut Polaroid film. A sufficient variety of lenses should be provided so that either a large model or a smaller local area may use the full size of the film.

Motion pictures are by far the most satisfactory method of recording a flow situation. Slow-motion pictures are especially useful in observing transient conditions.

To provide an accurate descriptive photograph of hydraulic models, the camera should be as far away as practicable to produce a more accurate silhouette of the model. In close-up camera positions, the passages in the model may be obscured by the thickness of the model.

Mirrors—Mirrors above the table may be used to provide the proper view of the model with the camera at a location that is convenient for manipulation. Large front-surfaced mirrors are desirable but ordinary back-surfaced mirrors usually give satisfactory photographs despite the reflection from the front surface. In making motion pictures, the mirror-camera system should be set up so that the longest dimension of the movie film frame lines up with the longest dimension of the water table.

Lights—At HDL, a bank of fluorescent lamps is placed under the water table. A sheet of translucent plastic is put between the lamps and table to diffuse the light. Grid lines are drawn on the plastic. Both the fluorescent lamps and the plastic are removable, so that parallel light for the shadowgraph can be introduced. Photoflood lamps are used for the absorption-visualization method (Appendix D) of evaluating flow.

Small lights (the small circles in figure 14) are used to indicate the position of pitot tubes. The light is successively placed at each pitot tube position and recorded photographically by multiple exposure. The room must be darkened sufficiently to permit multiple exposures of the same negative. The lines within the circles show the alignment of the pitot tube.

E2. FLOW MEASURING INSTRUMENTS

A small pump can be used for each particular flow. The measurement of flow by a rotameter has been found to be very satisfactory.

A pitot tube can be used in the water flow to obtain the velocity distribution. From this and depth measurements, the volume flow can be computed.

E3. DEPTH-MEASURING DEVICES

Water depth is analogous to density in the compressible gas, hence, its measurement is important in quantitative studies. Three methods have been used to make this measurement: (1) the probe method, (2) photogrammetry, and (3) the pressure method.

Probe-Method of Depth Measurement—A sharp pointed probe can be used to measure water depth. A micrometer screw lowers the probe until it contacts the surface of the water. Contact may be indicated by the flashing of a neon lamp when the lamp circuit is completed by the contact of the probe with the water surface. The probe is usually mounted on a sliding member resting on a cross bar that in turn travels on rails mounted on the edges of the tank. The probe is a very useful device to check the leveling of the water table. Still water in the table provides a horizontal reference surface to which the table surface can be compared by use of the probe.

Photogrammetry—The depth of the water can be measured by using an adaptation of the aerial mapping technique used to obtain contour maps of the surface of the earth. HDL has sponsored the building of such photogrammetry apparatus at the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. This device has been delivered and is being evaluated. A report is in preparation on the subject by BRL. Professor Mann of the Massachusetts Institute of Technology has reported on stereophotogrammetry (ref E1).

Pressure Method of Depth Measurement—The depth of the water can be determined by measuring the static pressure of the water. Holes in the model are used to communicate with the pressure measuring device or static holes can be provided on a pitot probe.

E4. PRESSURE MEASURING DEVICE

As previously noted, pressure measuring devices are used to measure water velocity and depth. Among instruments used are dual-liquid manometers, and inclined manometers. Microscopes have been used as an aid in making readings.

Dual-Liquid Manometer—Since water pressures are to be measured, it is quite easy to make connections to a U-tube manometer using water-filled lines. This has the effect of putting the manometer in an atmosphere of water, so to speak. The deflection of the manometer in response to a given pressure is inversely proportional to the difference between the density of the manometer fluid and the density of water. Large manometer deflections for small pressures may be achieved by using as a manometer fluid, a liquid of density near the density of water.

At HDL, a dual-liquid manometer was built using n-butyl phthalate as the manometer liquid. The density of n-butyl phthalate is only 4 percent greater than that of water, so that a pressure equivalent to 1 in. of water on an air-water manometer produces a deflection of 25 in. on the water-phthalate manometer. The manometer was not satisfactory because of uneven wetting of the manometer tube. It should be possible to overcome this problem by using an air-lock between the two fluids, but the project was not continued.

Inclined Manometer—An inclined water-air manometer in which the manometer fluid is actually air, and water-filled connecting lines extend to the water table, was found to be a reasonably satisfactory pressure measuring device for water table work. A large amount of wetting agent should be used in the manometer. Capillary effects can be much greater than the pressures measured unless the system is effectively rinsed with the wetting agent.

In this device water is sucked up from the table in two inclined tubes. The relative position of the water-air boundary in the tubes indicates the relative pressures existing at the ends of the tubes in the water table. The air pressure is equalized by connecting the upper ends of the tubes together, forming the familiar U-tube, but in an upside-down inclined position.

Two disadvantages of inclined tubes are that the magnification that is possible is limited and considerable water must flow into the system to produce the relatively large deflections that are inherent with the instrument, causing time delays in readings.

Microscope Reading of Air-Water Manometer—There are two main approaches that may be taken in measuring pressures with manometers. One approach is to magnify the deflection of the manometer as in the inclined water-air manometer. The other approach is to keep the manometer vertical and read the relatively small deflection with a microscope. This latter course was found to be the more rewarding. The measuring system requires relatively little flow from the measuring point, and it is quite easy to read within one or two thousandths of an inch of water with the proper magnification.

E5. REFERENCES

(E1) R. W. Mann, "Stereophotogrammetry Applied to Hydraulic Analogue Studies of Unsteady Gas Flow," Report No. 8543-1, Department of Mechanical Engineering, Massachusetts Institute of Technology, March 30, 1962.

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FLUID AMPLIFICATION—10. Use of the Hydraulic Analogy in the Study of Fluid Interaction Devices-- Ralph G. Barclay, Allen A Bowers, John G. Moorhead
TR-1098, 15 April 1963, 38 pp text, 27 illus. Department of the Army Proj 5N03-01-003, OMS Code 5010.11.71200, HDL Proj 31100, UNCLASSIFIED Report

The advantages of using the hydraulic analogy to study compressible gas flow in fluid interaction devices are discussed. The mathematical basis of the analogy is summarized, and limitations in its use are pointed out. Various practical aspects concerning operation of an analogy facility are reviewed.

Four hydraulic-analogy studies are briefly described: subsonic diffuser performance, three-stage closed-system bistable fluid-flow amplifier performance, quantitative measurement of switching flow required by a bistable fluid amplifier, and blocked-output-channel and stream-attachment characteristics in fixed and adjustable models of bistable elements.

Abstracts of seventeen references regarding the theory and application of the hydraulic analogy are given.

1. Fluid Amplifiers
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FLUID AMPLIFICATION—10. Use of the Hydraulic Analogy in the Study of Fluid Interaction Devices-- Ralph G. Barclay, Allen A Bowers, John G. Moorhead
TR-1098, 15 April 1963, 38 pp text, 27 illus. Department of the Army Proj 5N03-01-003, OMS Code 5010.11.71200, HDL Proj 31100, UNCLASSIFIED Report

The advantages of using the hydraulic analogy to study compressible gas flow in fluid interaction devices are discussed. The mathematical basis of the analogy is summarized, and limitations in its use are pointed out. Various practical aspects concerning operation of an analogy facility are reviewed.

Four hydraulic-analogy studies are briefly described: subsonic diffuser performance, three-stage closed-system bistable fluid-flow amplifier performance, quantitative measurement of switching flow required by a bistable fluid amplifier, and blocked-output-channel and stream-attachment characteristics in fixed and adjustable models of bistable elements.

Abstracts of seventeen references regarding the theory and application of the hydraulic analogy are given.

1. Fluid Amplifiers
2. Hydraulic Systems Design
3. Pneumatic Systems Design
4. Water Table

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