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[54] **LIQUID FLUIDIC DEVICE**

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[52] **U.S. Cl.** **137/836,** 137/823, 137/841, 137/837, 137/842, 137/13

[51] **Int. Cl.** **F15c 1/18**

[58] **Field of Search** 137/806, 807, 822, 823, 137/836, 837, 841, 842, 13

[56] **References Cited**

UNITED STATES PATENTS

3,234,955	2/1966	Augel	137/842
3,455,317	7/1969	Smith	137/823 X
3,574,309	4/1971	Kinner	137/842 X
3,667,489	6/1972	Blaiklock et al.	137/837

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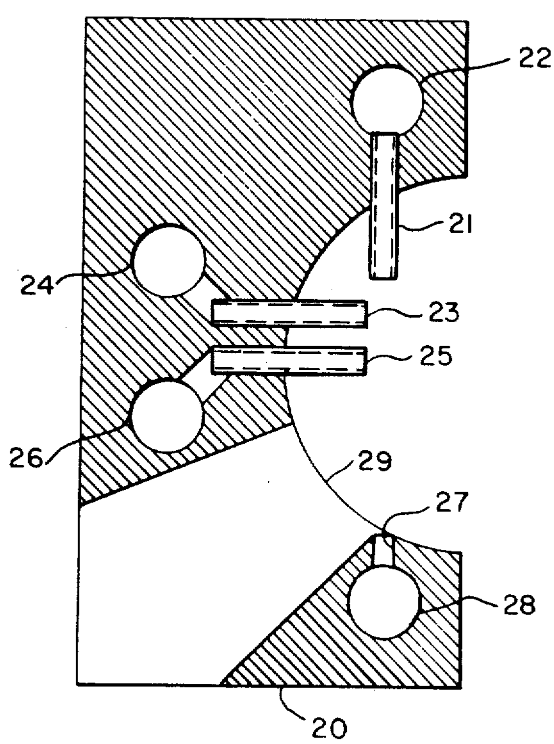
[57] **ABSTRACT**

A liquidic (liquid fluidic) control element which operates with laminar liquid jets. The element uses a liquid control jet operating with a Reynolds number of less than 550 which when directed at the emitter jet deflects it inward towards the control jet, opposite to that found in conventional fluidic devices. Since this mode of deflection requires low control jet flow rates, high amplification and/or fan-out are inherently achieved. Low power requirements make the invention particularly suitable for logic circuits which can be constructed from the basic NOR element.

14 Claims, 4 Drawing Figures



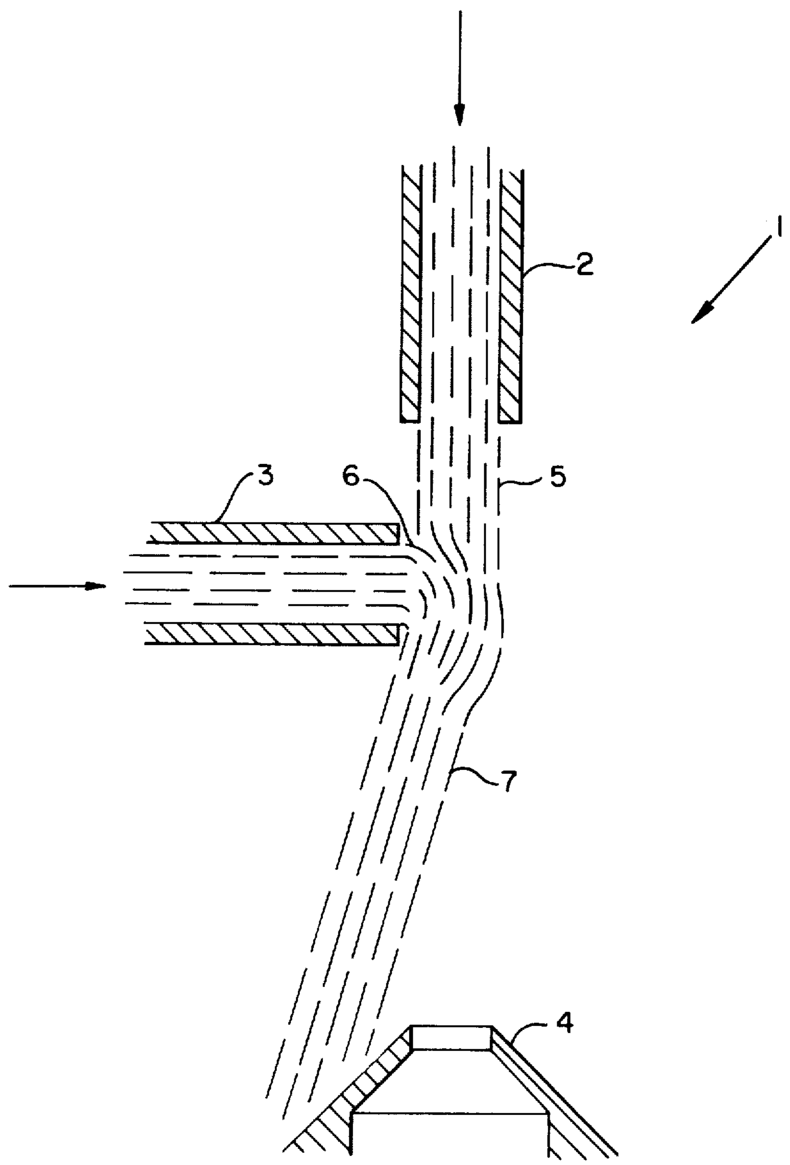


FIG. 1

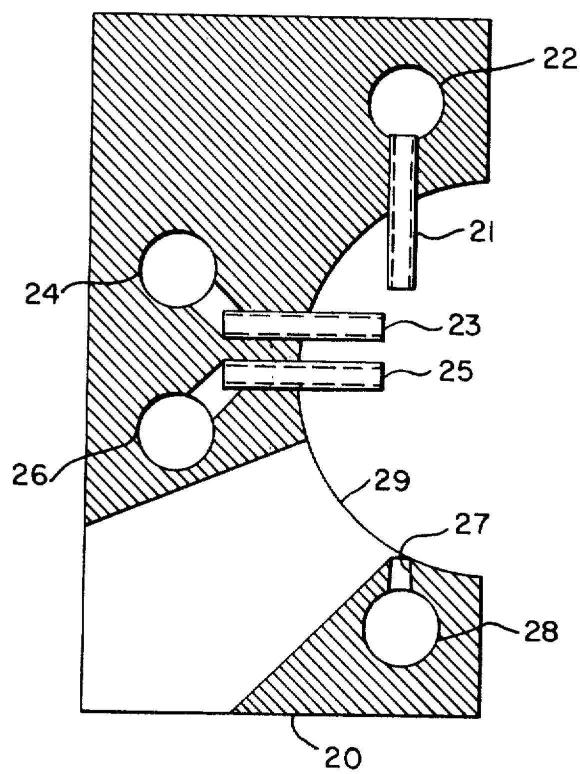
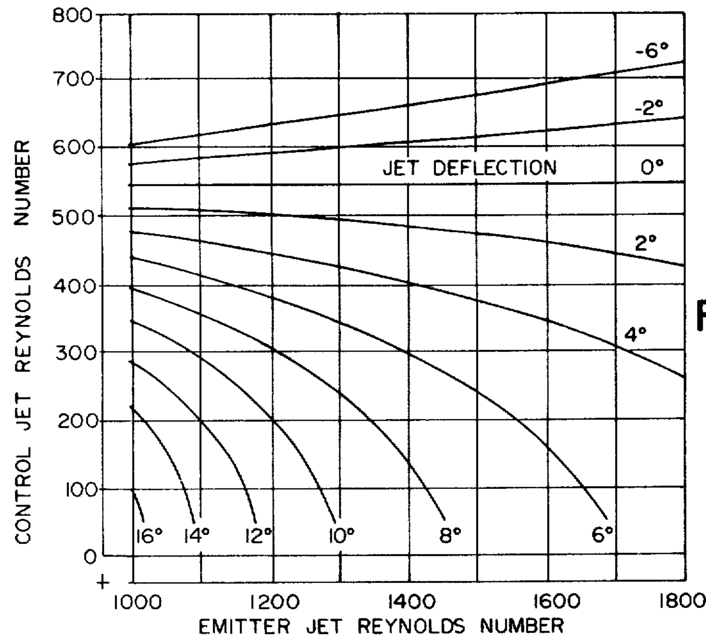


FIG. 2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800
700
600
500
400
300
200
100
0
-6°
-2°
JET DEFLECTION
0°
2°
4°
16°
14°
12°
10°
8°
6°
1000
1200
1400
1600
1800
EMITTER JET REYNOLDS NUMBER

FIG. 3

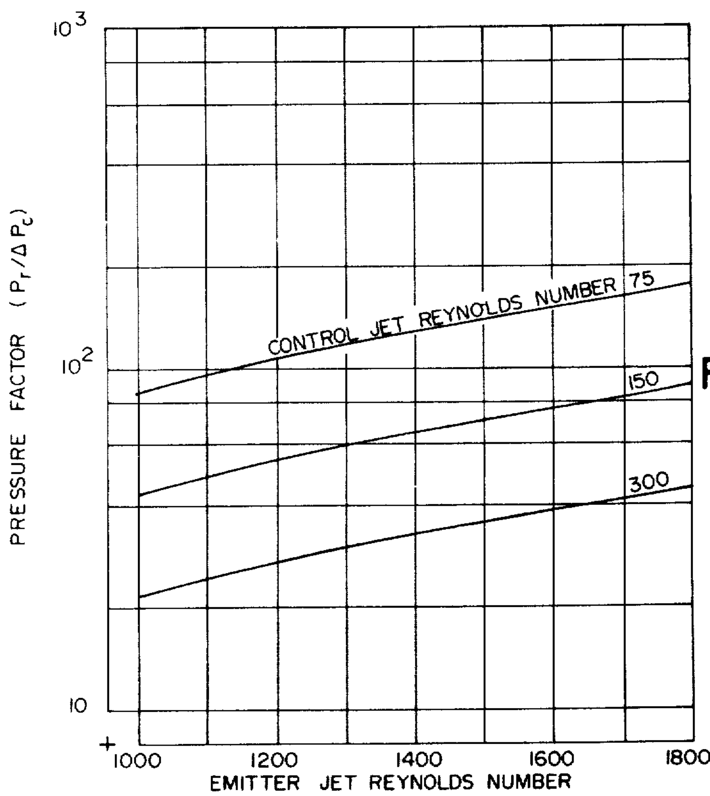
PRESSURE FACTOR (P_r / Δ P_c)
10^3
10^2
10
CONTROL JET REYNOLDS NUMBER 75
150
300
1000
1200
1400
1600
1800
EMITTER JET REYNOLDS NUMBER

FIG. 4

LIQUID FLUIDIC DEVICE

BACKGROUND OF THE INVENTION

This invention relates to a fluid operated control device, and more particularly to a fluid operated control device wherein both the control fluid and the controlled fluid are a liquid flowing in the laminar regime.

At present, hydraulic systems are controlled by one or more of the following hybrid systems: mechanical-hydraulic, electromechanical-hydraulic; or pneumatic-hydraulic. The use of fluidic elements for hydraulic control provides a number of potential advantages over the other hybrid systems. Fluidic elements provide greater reliability, shorter response times, reduced cost, are more easily fabricated, and are less sensitive to environmental conditions. A fluidic element using the working fluid for control has the additional advantage of eliminating interfacing.

Although many basic concepts of fluidics are equally applicable to both gas and liquid, there are important differences which do not allow a practical hydraulic fluidic control system to be designed as readily as a pneumatic fluidic system or a hybrid system. One important difference is that liquid as a fluid is a more costly commodity than air. For this reason it is important that the control element has high amplification and/or fan-out and also low power requirements. Also most pneumatic fluidic devices operate under submerged turbulent flow conditions, and the resultant diffusion of the jet produces poor pressure recovery, which is not the case with a liquid operated device of the present type.

The ability to deflect a laminar fluid jet away from the control jet has been reported in the literature. These investigations showed inherently higher signal-to-noise ratios and lower response times using laminar rather than turbulent jets, and faster signal transmission using liquids rather than the conventional air medium. The laminar jet has been avoided in current pneumatic element design since it had been found difficult to preserve laminar conditions in the jet when it was deflected by the impingement of a control jet and also because it was difficult to reattach a laminar jet to a wall. Since these conditions are not applicable when using a liquid control medium, advantage can be taken of the fact that a laminar jet results in considerably higher pressure recovery since the diffusion of the jet is much less.

Prior to the present invention, the deflection of a jet was effected either by velocity effects (momentum interchange), or by pressure effects. In a momentum interchange fluidic device the momentum of the main jet is modified by the momentum of the control jet resulting in a deflected attitude. This type of device can operate either digitally or proportionally. If a single receiver for the main jet is utilized and venting is accomplished, then any deflection greater than one full diameter will result in a loss of signal at the receiver, resulting in a digital mode of operation.

It is commonly accepted that the results of the impingement of two jets can be predicted by means of jet momentum flux interchange. This theory has been reported in the literature many times, and has been used successfully with high-speed jets.

However, it has been found that momentum interchange does not adequately predict the behavior of interacting liquid jets operating at low Reynolds numbers. It was discovered that when the emitter jet operates in the laminar region the jet could not only be deflected away from the control jet (using relatively high control jet flow rates as compared to the emitter jet) but it could also be deflected toward the control jet by using low control jet flow rates as compared to the emitter jet. The present invention exploits this phenomena providing a fluidic device with inherently high gain since a large difference in flow of the control jet relative to the emitter jet is required to achieve the desired mode of operation.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a fluidic control device in which the control fluid and the emitter fluid are liquids operating under laminar conditions.

Another object is to provide a fluidic device having a unique mode of operation wherein the emitter jet is deflected by the control jet inward towards the control nozzle.

Another object is to provide a fluidic device which has relatively high amplification and/or fan-out, high pressure recovery and low power requirements.

It is another object to provide a liquid fluidic device capable of providing all digital logic functions.

It is another object to provide a liquid fluidic device capable of proportional operation.

The present invention essentially comprises an emitter nozzle for coupling to a liquid supply source and operative to issue a coherent and laminar liquid emitter jet, a control nozzle adapted to issue a liquid control jet having a Reynolds number less than 550 operative to deflect the emitter jet inward towards the control nozzle, and receiver means spaced downstream from the emitter for receiving the emitter jet.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a generalized sectional view of a liquid fluidic device illustrating the mode of deflection of the present invention under requisite conditions of flow.

FIG. 2 is a sectional side view of one embodiment of the invention in the form of a NOR logic element.

FIG. 3 illustrates graphically typical relationships between emitter jet deflection, control jet Reynolds number and emitter jet Reynolds number.

FIG. 4 illustrates graphically typical relationships between pressure factor or gain, control jet Reynolds number and emitter jet Reynolds number.

DESCRIPTION OF PREFERRED EMBODIMENTS

With reference to FIG. 1, the fluid element 1 comprises an emitter nozzle 2, a control nozzle 3 and a receiver 4. In operation, a liquid is supplied to the emitter nozzle 2 such that the emitter nozzle issues a laminar and coherent jet 5. In the absence of a control jet the emitter jet is received by the receiver 4. When the control nozzle 3 issues a coherent laminar jet 6 with Reynolds number less than 550, the emitter jet 5 is deflected inward towards the control nozzle. The receiver 4 is positioned such that the emitter jet 7 when deflected by control jet 6 is not received by the receiver.

To provide the desired mode of deflection the control jet Reynolds number must be less than approximately 550 since above approximately 550 momentum effects will dominate and the device will operate in the conventional mode, with deflection away from the control jet. FIG. 3 shows typical control and emitter flows required to develop given deflection angles. The threshold of flow is the lower limit for effecting deflection and provides maximum deflection angles. Preferably however, the control jet Reynolds number will be greater than 50, since below this value changes in environmental conditions tend to cause erratic operation. It was found that for reliable operation, low power requirements, and maximum amplification and fan-out, a suitable range for control jet Reynolds number is 50 to 150, particularly when operating with an emitter jet Reynolds number from 100 to 1,800. It was further found that control jet Reynolds numbers greater than 150 also resulted in satisfactory operation and it appears evident that any value less than approximately 550 may be practical in certain applications.

As previously indicated, control jet Reynolds numbers greater than approximately 550 yield conventional mode deflection which is not presently claimed as inventive. FIG. 3 illustrates that a given fluidic element may operate in the conventional mode (negative deflection angles in FIG. 3) as well as in accordance with the present invention (positive deflection), depending on the flow conditions.

As stated previously, this invention requires that the emitter nozzle operates to issue a laminar and coherent jet. The requirement for a laminar emitter jet can be provided with a Reynolds number of less than 2,000. A particularly useful range of emitter jet Reynolds numbers was found to be 1,000 to 1,800. The relationship of this range of Reynolds numbers with other parameters is shown in FIGS. 3 and 4.

FIG. 2 illustrates an embodiment of the invention suitable as a NOR logic element. The liquid fluidic device comprises an emitter nozzle 21 which is supplied with a liquid through an inlet 22, control nozzles 23 and 25 with inlets 24 and 26, respectively, and a receiver 27 that communicates with outlet 28. Second receiver means or sump 29, which is integral with the body member 20, is adapted to receive the emitter jet issuing from the emitter nozzle 21 when it is deflected by a control jet issuing from either of the control nozzles 23 and 25.

For optimum operation in the digital mode, the distance from the emitter exit to the control-emitter interaction zone should be greater than 1.5 emitter nozzle diameters. It was found that when this distance was less than 1.5 diameters, impingement of the control jet on the main jet caused a smooth transition in the interaction region where the main jet could tend to remain deflected even when the control flow was stopped. No advantage is gained by increasing this distance more than two diameters. The only disadvantage is that the overall length of the device will be increased. In view of the above the preferred distance from the emitter nozzle exit to the interaction zone is two emitter nozzle diameters with any additional control nozzles spaced downstream therefrom and oriented in such a manner that flow from two control nozzles do not neutralize each other.

It is not necessary that the emitter nozzle provide fully developed flow for satisfactory operation and therefore emitter length should be as small as possible, consistent with adequate aiming of the jet, in order to minimize both the power requirement and the overall size of the device.

The distance between the emitter and receiver is not critical other than being sufficient to permit total deflection of the emitter jet from the receiver so that the device may operate in the NOR mode. A distance of five jet diameters was found to be sufficient for the greatest angular deflection obtainable. Preferably the distance is as short as possible to minimize switching time.

The receiver length should be as short as possible, and should expand quickly and smoothly to minimize pressure losses. The actual geometry will be a matter of choice based on the system requirements, avaiable fabrication techniques, etc.

Deflection was found on the basis of experimental data to have a high correlation (90 percent) with Reynolds numbers. FIG. 3 presents this data in a form convenient for design purposes.

Optimum results are attained when the control jet intersects the emitter jet at an angle of approximately 90°. It was found that the device operated in the desired manner (deflection toward the control jet side) when the angle between the two jets varied from 45° to substantially 90°. At angles less than 45°, the jets tended to interact and coalesce into a single jet directed away from the control jet side, similar to a conventional beam-deflection device. As the angle approached 90°, less and less control flow was required to develop an equal deflection.

The control exit should be as close as possible to the main jet in order to minimize the control flow requirements (the further away, the greater the flow required to obtain reliable interaction), and yet far enough away to permit the rapid return to the undeflected mode. It was found that a distance of 0.010 to 0.015 inches from the jet was optimum and that this distance was essentially constant and independent of the size of the jet.

The sump for the deflected jet should be as large as possible to prevent the receiver from submerging, which would reduce pressure recovery and cause spurious operation.

It was found that a weak optimum effect is obtained when the diameters of the emitter, control and receiver were the same size. In view of this and the obvious fabrication advantages, it is preferable that the nozzle passage diameters be uniform throughout the device.

It was further found that nozzles having square shaped passages operated in the same manner as cylindrical passages.

The liquid fluidic element as shown in FIG. 2 is designed to operate with the emitter jet issued substantially vertically downward. With a device using water and having nozzle passage diameters of 0.02 inches, satisfactory sumping and control was obtained when the alignment was within 15° from the vertical. Smaller devices operating at higher velocities are more tolerant of deviations from vertical orientation than larger devices.

Experiments showed that the device is relatively insensitive to vibration (high frequency, low amplitude excursion) but susceptible to shock (low frequency, high amplitude excursion) particularly in the larger size devices where the mass of the fluid is large and the velocities low.

Since liquids have essentially no capacitance, and relatively high resistance and inductance (fluid inertia), the impedance is relatively high compared with air fluidic devices, thereby minimizing the necessity of impedance matching.

The primary criteria for the design of a digital fluidic device operating with a liquid are: supply power requirement, size, switching time, and pressure recovery.

The power needed to operate the device is essentially a function of the working fluid, and inversely proportional to size. The power requirement is based on the supply pressure required to maintain the appropriate Reynolds number flow, the volumetric flow rate, and the internal losses due to the geometry of the device, including entrance losses, constriction losses, flow losses, etc. The power required is a function of the emitter jet Reynolds number, cubed; and inversely proportional to the diameter of the jet.

The size of the device will be a function of the distance from the emitter to the control nozzle, the length of the jet from the interaction region to the receiver, the nozzle lengths, and the geometry of the inlets or outlets to or from the nozzles.

Switching time is a function of the velocity of the emitter jet and distance from the interaction region to the receiver. More specifically, shorter switching times are obtained with higher emitter jet velocities and shorter distances to the receiver. Decreasing the emitter jet diameter increases jet velocity and therefore decreases switching time.

The pressure in the receiver is proportional to the square of the ratio of the main jet Reynolds number to the jet diameter. The ratio of the pressure in the receiver to that required to assure control is an equally important consideration since it is an indication of the number of elements that may be driven by the output of one element, or the fan-out of the device.

FIG. **4** shows the pressure factor or gain (receiver pressure/Δcontrol pressure) related to emitter and control jet Reynolds number. The values given are based on emitter and control nozzle passage length of **10** nozzle passage diameters.

Lower power requirements for an equivalent Reynolds number, and lower susceptibility of failure due to contamination can be obtained by increasing the size of flow passages, but as a result switching speed, overall size and pressure recovery are adversely affected. Since there is no single combination that permits maximization of all parameters, it becomes necessary to rank operating characteristics by priority and optimize the design for the particular application desired.

For logic circuit operation, total power requirements, switching times, and fan-out become the major items of consideration due to the potentially large number of devices required for a single system. The choice of fluid is essentially between water and hydraulic oil. If water is selected, small devices can be designed with power requirements of approximately two orders of magnitude less than conventional air fluidic devices. However, the maximum switching speed that can be obtained is approximately 7 milliseconds. If higher speed is essential, then oil should be used, which requires an order of magnitude more power than necessary when using air devices, due to the necessity of providing an order of magnitude more supply pressure.

Following are examples of liquid fluidic devices of the type shown in FIG. **2**, giving details of design.

For a logic control system in which the working fluid is water and for which a switching time of 8 milliseconds is acceptable, suitable design parameters are: Nozzle passage diameters, (emitter, control and receiver) 0.02 inches; emitter and control passage length, 0.20 inches; emitter jet deflection angle 6°; (note FIG. **3**) emitter jet Reynolds number, 1,670; control jet Reynolds number, 95; distance from emitter to control nozzle centerline, 0.04 inches; distance from control nozzle to emitter jet axis, 0.020 to 0.025 inches; free jet length from control nozzle to receiver, 0.20 inches (0.02 cot 6° = 0.191 inches). Fan-out of the device is approximately **18.** The pressure factor is approximately 150 and the power requirement approximately 9×10^{-4} watts.

As another example, consider high speed the prime criterion with power requirements secondary. For these requirements the working fluid selected in a hydraulic oil (MIL-H-5606). Suitable design parameters are: Nozzle passage diameter, 0.020 inches; emitter Reynolds number, 1,200; control Reynolds number 200; deflection angle, 10°, emitter nozzle passage length, 0.20 inches; distance from control nozzle to receiver, 0.10 inches. The switching speed obtainable is 0.53 milliseconds and the pressure in the receiver is 1.97 psi. The power requirement is approximately 0.7 watts.

An experiment was conducted to determine the number of elements that could be controlled by the output of one element. Using two modules consisting of 8 elements each, it was found that one element could control the remaining 15, indicating a fan-out capability for the device of at least 15.

Logic circuits were constructed using liquid fluidic NOR elements of the type shown in FIG. **2** including a NOT module, an AND, OR and bistable element, and a single stage binary counter. Using liquid as the operating fluid, time delays can be conveniently obtained with a suitable length of conduit. To obtain a delay in pneumatic fluidics, either a capacitance or a resistance would be required, which in turn would change the impedance. Since the liquid fluidic device is essentially impedance insensitive, a resistance in the form of a long conduit can be used with no deleterious effects.

The fluidic device was also designed to oscillate by feeding back the output of the receiver to the control port. It was found that the period of oscillation was a direct function of the emitter jet flow, but the "time on/time off" ratio was proportional to the amount of fluid fed back from the receiver to the control nozzle. By metering this amount, flow into the receiver could be controlled from approximately 20 to 80 percent of the emitter flow. This effect can be applied to provide controlled variable sampling of liquid.

The transport time between the receiver and the control port is also a function of the compressibility of the working fluid in that this parameter affects the speed of propagation of the pressure wave. This allows the device to be used for the measurement of compressibility and bulk modulus of a liquid, to determine, for example, the dissolved gas content.

The device was also used for flow measurement. Devices with nozzle passage diameters of 0.125 were assembled with an interconnecting conduit 48 inches long. Flow is measured by counting the frequency of oscillation.

The invention also provides a device that will operate in the proportional mode since the angle of deflection is a function of control jet flow, as illustrated in FIG. 3. With reference to FIG. 1 it can be seen that pressure in the receiver 4 will vary from a low value when a relatively low control jet flow is supplied, that is with a large emitter jet deflection, to a greater value as the control jet flow is increased and momentum effects decrease the angle of emitter jet deflection. It will be understood that the receiver need not necessarily be positioned coaxially downstream from the emitter as shown in FIG. 1, but may be positioned so that maximum pressure at the receiver is obtained when the emitter jet is partially deflected.

Other embodiments and applications of the present invention will occur to those skilled in the art.

What is claimed is:

1. A liquid fluid operated control device comprising:

a. an emitter nozzle for coupling to a liquid supply source and operative to issue a coherent and laminar liquid emitter jet;

b. a control nozzle adapted to issue a liquid control jet having a Reynolds number less than 550 operative to deflect the emitter jet inward towards the control nozzle; and

c. receiver means spaced downstream from the emitter for receiving the emitter jet.

2. The apparatus of claim 1 wherein the control jet has a Reynolds number of from 50 to 550.

3. The apparatus of claim 2 wherein the control jet has a Reynolds number of from 50 to 150.

4. The apparatus of claim 1 wherein the emitter jet has a Reynolds number of less than 2,000.

5. The apparatus of claim 4 wherein the emitter jet has a Reynolds number between 1,000 and 1,800.

6. The apparatus of claim 1 wherein the receiver means is positioned coaxially downstream of the emitter nozzle for receiving the non-deflected emitter jet.

7. The apparatus of claim 6 comprising two control nozzles defining a NOR logic element.

8. The apparatus of claim 1 wherein the control jet intersects the emitter jet at a distance greater than 1½ emitter nozzle diameters downstream from the emitter nozzle.

9. The apparatus of claim 1 wherein the control jet intersects the emitter jet at an angle between 45° and substantially 90°.

10. The apparatus of claim 9 wherrein the angle of intersection is substantially perpendicular.

11. The apparatus of claim 1 wherein the distance of the outlet of the control nozzle to the emitter jet is from 0.01 to 0.015 inches.

12. The apparatus of claim 1 comprising additional receiving means for receiving the deflected emitter jet.

13. The apparatus of claim 1 wherein the diameter of the emitter nozzle, control nozzle and receiver inlet are substantially equal.

14. The apparatus of claim 1 wherein the emitter jet is directed substantially vertically downward.

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