2-1-1972

Studies of bistable fluid devices for particle flow control

Gerald H. Hogland
Portland State University

Follow this and additional works at: https://pdxscholar.library.pdx.edu/open_access_etds

Part of the Dynamics and Dynamical Systems Commons, Fluid Dynamics Commons, and the Mechanics of Materials Commons

Let us know how access to this document benefits you.

Recommended Citation
https://doi.org/10.15760/etd.739

This Thesis is brought to you for free and open access. It has been accepted for inclusion in Dissertations and Theses by an authorized administrator of PDXScholar. Please contact us if we can make this document more accessible: pdxscholar@pdx.edu.

Title: Studies of Bistable Fluid Devices for Particle Flow Control.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

[Signatures]

Pah I. Chen, Chairman

Harry J. Whittaker

Jack C. Riley

Robert W. Rempfer

This study was directed toward the development of a bistable wall attachment Flip-Flop device which was capable of directionally controlling particle flow. The particles were transported by a fluid stream which was under the influence of wall attachment. The dominant criteria in the development of the device was the achievement of the highest recovery of particles at the active output, without destroying the wall attachment of the fluid stream.

The experiment was conducted in several distinct stages; each of which was concerned with at least one aspect of wall attachment or particle flow. Results derived from one test were used to develop the criteria for the next experimental arrangement.
Two experimental models were constructed: one of plywood with only one attachment wall, and one of plexiglas which had two attachment walls and was bistable. The plywood model was used in testing wall attachment and particle recovery as a function of the attachment wall angle. From these tests it was concluded that the optimum wall angle was 18 degrees from the center line of the device. Observations of particle action in the plywood model led to the incorporation of additional features in the plexiglas model. They were: an extended nozzle, the elimination of the separation bubble, and the development of smooth transitions at the corners.

The plexiglas model was used to investigate optimum splitter location, the effect of jet velocity on recovery efficiency, the effect of vents on the performance of the device, and the performance of the device using a water jet. In the last stages of testing, moving parts and additional output features were used in conjunction with the bistable device to improve the collection efficiency. Some observations resulting from the data gathered in the various tests include:

1. The higher the jet velocity, the greater the wall attachment.

2. The higher the density and viscosity of the fluid stream the greater the recovery of particles at the active output.

3. Particles with large inertial forces were controlled less by the attached jet stream.

4. The addition of vents in the device may produce greater particle recovery.

5. The use of moving parts and variations in the output leg design can produce 100 percent particle recovery.
This study indicated that it was possible to control the directional flow of particles with the bistable wall attachment device which was developed. However, the pure fluid bistable device could not achieve 100 percent recovery of particles. The addition of moving parts or variations in output leg design can produce 100 percent recovery of the particles. The use of a bistable device could provide simplicity, reliability and adaptability in transporting materials for industrial processes.
STUDIES OF BISTABLE FLUID DEVICES FOR PARTICLE FLOW CONTROL

by

GERALD H. HOGLAND

A thesis submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
APPLIED SCIENCE
Portland State University
1972
TO THE OFFICE OF GRADUATE STUDIES:

The members of the Committee approve the thesis of

Gerald H. Hogland presented May 17, 1972

Pah I. Chen

Harry J. White

Jack C. Riley

Robert W. Rempfer

APPROVED:

Nan-Teh Hsu, Head, Department of Applied Science

David T. Clark, Dean of Graduate Studies
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II GENERAL METHODS AND MATERIALS</td>
<td>9</td>
</tr>
<tr>
<td>III DETERMINATION OF WALL ATTACHMENT AND WALL ANGLE</td>
<td>14</td>
</tr>
<tr>
<td>IV DETERMINATION OF NOZZLE EFFECT OF WALL ATTACHMENT</td>
<td>20</td>
</tr>
<tr>
<td>V TESTING A BISTABLE WALL ATTACHMENT DEVICE</td>
<td>31</td>
</tr>
<tr>
<td>VI TESTING A VENTED WALL ATTACHMENT DEVICE</td>
<td>48</td>
</tr>
<tr>
<td>VII PERFORMANCE OF THE BISTABLE DEVICE USING A WATER JET</td>
<td>52</td>
</tr>
<tr>
<td>VIII MAKING A BISTABLE DEVICE MORE EFFICIENT FOR PARTICLE FLOW CONTROL</td>
<td>54</td>
</tr>
<tr>
<td>IX SUMMARY AND CONCLUSION</td>
<td>62</td>
</tr>
</tbody>
</table>

REFERENCES | 64 |
REFERENCES NOT CITED | 65 |
APPENDICES | 66 |
ACKNOWLEDGMENT

Nothing is as important as the people we know, and I have been fortunate to have met special people at Portland State University.

I am indebted to Dr. Nan-Teh Hsu, Dr. Harry White, Mr. Jack Riley and Mr. Carl Fanger for the help and guidance they have given me in my academic career. I owe special thanks to Dr. Pah Chen, who has given me encouragement and advice not only in this study, but throughout my studies at Portland State and has constantly served to excite my imagination.

I would also like to acknowledge the support of the Tektronix Foundation during this study, and also the help given to me by the Physics shop under the direction of Jack Janacek. Thanks also go to Donna Mikulic for her help in formalizing this paper.

Lastly, I would like to express my gratitude to my family and to my wife, Julie, who have supported me in all my endeavors.
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Jet Spread for Non-Converging Nozzle at Adjusted Attachment Wall Angles</td>
<td>18</td>
</tr>
<tr>
<td>II</td>
<td>Jet Spread for Converging Nozzle at Adjusted Attachment Wall Angles</td>
<td>26</td>
</tr>
<tr>
<td>III</td>
<td>Particle Distribution at Two Flow Rates and Adjusted Attachment Wall Angles</td>
<td>28</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Symbol of a Flip-Flop and Its Truth Table</td>
</tr>
<tr>
<td>II</td>
<td>Simple Design Representation of a Flip-Flop</td>
</tr>
<tr>
<td>III</td>
<td>Natural Jet Spread and Vortice Formation</td>
</tr>
<tr>
<td>IV</td>
<td>Wall Attachment to an Adjacent Wall</td>
</tr>
<tr>
<td>V</td>
<td>Sequence of Controls and Outputs used in Producing Truth Table</td>
</tr>
<tr>
<td>VI</td>
<td>Large Scale Plywood Wall Attachment Device</td>
</tr>
<tr>
<td>VII</td>
<td>Large Scale Plywood Model with Converging Nozzle</td>
</tr>
<tr>
<td>VIII</td>
<td>Plexiglas Model with Fixed Walls and Controls</td>
</tr>
<tr>
<td>IX</td>
<td>Experimental Plywood Model</td>
</tr>
<tr>
<td>X</td>
<td>Example of Dusted Track Experiment</td>
</tr>
<tr>
<td>XI</td>
<td>Model of Converging Nozzle and Recovery Area Definition</td>
</tr>
<tr>
<td>XII</td>
<td>Plywood Model with Converging Nozzle</td>
</tr>
<tr>
<td>XIII</td>
<td>Complete Experimental Plywood Apparatus</td>
</tr>
<tr>
<td>XIV</td>
<td>Wall Attachment Verses Wall Angle for Converging and Non-Converging Nozzle</td>
</tr>
<tr>
<td>XV</td>
<td>Curved Wall and Off-Set Wall</td>
</tr>
<tr>
<td>XVI</td>
<td>Example of Particle Interaction with Wall</td>
</tr>
<tr>
<td>XVII</td>
<td>Location of Splitter</td>
</tr>
<tr>
<td>XVIII</td>
<td>Device Showing Splitter and Controls</td>
</tr>
<tr>
<td>XIX</td>
<td>Cyclone Bins used to Catch Particles</td>
</tr>
<tr>
<td>XX</td>
<td>Air Supply and Adapter for Plexiglas Model</td>
</tr>
<tr>
<td>FIGURE</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>XXI</td>
<td>Cyclone Bin used to Catch the Particles from the Output</td>
</tr>
<tr>
<td>XXII</td>
<td>Splitter Distance Verses Particle Recovery</td>
</tr>
<tr>
<td>XXIII</td>
<td>Splitter Distance Verses Particle Recovery</td>
</tr>
<tr>
<td>XXIV</td>
<td>Splitter Distance Verses Average Particle Recovery</td>
</tr>
<tr>
<td>XXV</td>
<td>Pressure Differential Verses Recovery Efficiency</td>
</tr>
<tr>
<td>XXVI</td>
<td>Reverse Flow in the Passive Output Caused by Air Entrainment</td>
</tr>
<tr>
<td>XXVII</td>
<td>Splitter Location and Vortex Flow</td>
</tr>
<tr>
<td>XXVIII</td>
<td>Vented Device</td>
</tr>
<tr>
<td>XXIX</td>
<td>Pressure Differential Verses Recovery Efficiency</td>
</tr>
<tr>
<td>XXX</td>
<td>Lifted Leg Device</td>
</tr>
<tr>
<td>XXXI</td>
<td>Blocking Vane Device</td>
</tr>
<tr>
<td>XXXII</td>
<td>Guiding Vane Device</td>
</tr>
</tbody>
</table>
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Dimensions of the Plexiglas Device</td>
<td>67</td>
</tr>
<tr>
<td>II Flow Rate and Velocity as Related to Pressure Differential</td>
<td>68</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

This study was directed toward the development of a bistable wall attachment Flip-Flop device which was capable of directionally controlling particle flow. The particles were transported by a fluid stream which was under the influence of wall attachment. The dominant criteria in the development of the device was the achievement of the highest recovery of particles at the active output, without destroying the wall attachment of the fluid stream.

In the last dozen years there has been increased development in a new field of fluid control, which is known as fluidics. While some moving part control devices are considered under the term fluidics, it is assumed that pure fluidics describes control elements which contain no moving parts. There are three major areas which are included in fluidic control:1*

1. Analog
2. Digital
3. Modulated carrier

Fluidic analog elements encompass such devices as vortex resistors and proportional amplifiers. The output of analog devices, as defined by their name, has a proportional relationship to the input. Digital elements on the other hand, have outputs defined only by a "1" or "0".

*Numerical references superior to the line text refer to references
A "1" represents a presence of high flow and "0" represents low flow.

There are two distinct classes in the digital family; namely, devices which use wall attachment and devices which do not. The phenomenon of wall attachment will be discussed in some depth because it plays a fundamental role in this study. Modulated carriers include such devices as sensors and signal generators and are not strictly considered fluidic elements. Excellent examples of the various industrial applications of these different types of elements can be found in a paper by W. T. Rauch.¹

The earliest recording of a most basic fluidic phenomenon, that of wall attachment, is credited to T. Young on January 16, 1800, and is known by some as the "Young effect."² Henri Coanda, a Rumanian engineer, while working in Paris on one of the first jets, also recorded the phenomenon of wall attachment. He observed the fiery exhaust of his jet attach itself to a metal deflector plate and destroy the plane's fuselage.³ Subsequently, he patented a wall attachment device in 1934.⁴

Wall attachment is now referred to as the "Coanda effect" and will be described as such in the remainder of this study. A brief history of Coanda's work and its application is presented by Imants Reba in a paper titled "Applications of the Coanda Effect."³

The development of fluidics was not undertaken on a large scale until the late 1950's. The Diamond Ordinance Fuze Laboratory, now Harry Diamond Laboratories, in Washington, D.C., under government secrecy, developed the technology necessary to produce fluid logic elements. Many basic patents were issued to the men who were directly involved in those studies.

The earliest applications of fluidics, and still one of the major areas, is in the field of military use. Fluidics is now being adapted
in many areas of control and logic systems. Such companies as General Electric, Corning, Bowles and Norgren are producing fluidic elements which are capable of being integrated into control systems. A survey by D. C. Bain and P. J. Baker in the United Kingdom gives an enlightening view of the diversified application of fluidics and also some of the advantages in using fluidics. They estimate the market in the United Kingdom to be between 15 and 45 million dollars by 1975.

One of the key designs in fluidic logic is a digital element called a bistable wall attachment device. This element incorporates the "Coanda effect" to produce a logic gate which has moderate gain and also memory. Referring to the "1" and "0" output states, a truth table can be constructed defining O1, O2 as outputs and Cl, C2 as controls. Assume that there is a constant supply to the bistable Flip-Flop device. Refer to Figures 1 and 2 to relate the controls to the outputs. Note that a control in a Flip-Flop device can change the output state and the output state will remain constant even when the control is removed.

A simple explanation of the "Coanda effect" is given here. As a jet stream (either gas or liquid) flows freely out of a nozzle, vortices are formed which entrain the surrounding fluid into the spreading jet as in Figure 3. If this jet is near a wall, there is a restriction of the fluid entrainment which creates a relatively low pressure region causing the jet to be "held" or attached to the wall. When the wall is angled away from the jet center line, as in Fig. 4, the centrifugal force
of the curved jet is balanced by the pressure drop across the jet.

Bourque and Newman\textsuperscript{6} presented one of the first analyses of jet attachment to a parallel off-set wall and an inclined adjacent wall. K. Foster and N. S. Jones\textsuperscript{7} give some basic relationships between geometric parameters and wall attachment characteristics. Work has been done in the area of wall design, venting, pressure recovery and switching mechanisms by various authors including: T. Sarpkaya and J. M. Kirshner,\textsuperscript{8} S. Ozaki and Y. Hara,\textsuperscript{9} and P. A. Lush.\textsuperscript{10} There is also a numerical analysis of the "Coanda effect" by S. P. Chavez and C. G. Richards,\textsuperscript{11} which gives specific solutions to the Navier-Stokes equation.

A basic figure of an element capable of generating turbulent wall attachment can be seen in Fig. 2. Most industrial devices are under 2 inches by 2 inches by 1/4 inch in overall outside dimensions depending upon the particular manufacturer. The sequence which produced the truth table can now be followed in Fig. 5.

Fig. 5a shows a supply jet attached to output 01. When a control, C1, is introduced as in Fig. 5b, the "separation bubble" created by the relative low pressure is filled by the flow from the control, and the supply jet detaches from 01 and attaches to 02 as illustrated in Fig. 5c. If control C2 is activated (Fig. 5d), the process is reversed, and the jet attaches to 01 where it will remain attached. With the introduction of the vents, the bistable device will become load insensitive and the output can be completely blocked without causing an uncontrolled switching.\textsuperscript{9} The amount of flow necessary in the controls to switch the main jet depends upon the particular device geometry, the Reynolds number of the supply jet and the total supply flow.

The bistable wall attachment device developed in this study will
be referred to as a "Flip-Flop", this is consistent with the current industrial definition. The general application of a Flip-Flop is in logic and control circuit design. The output can be used as a control function for other fluidic elements, e.g., binary counters, or it can be interfaced to produce a required action, e.g., piston movement.

The aim of this study was to gather and present information necessary to produce a "Flip-Flop" on a dimensional scale much larger than is normally being used in fluidic control. This was done so that the "Coanda effect" could be used to control the directional flow of solid particles, which in essence constitutes a directional diverting valve with no moving parts necessary to switch outputs. This, however, did not limit the design of the device to non-moving parts. It was desirable to use simple moving parts to improve the device performance as defined by the percentage of particles recovered at the correct output. These moving parts were not used in lieu of the non-moving controls, and are not capable of switching outputs. The study was concluded with three modifications on the design of the device to produce an element which can perform the control function of a diverting valve and still remain as close to pure fluidic devices as possible.
Fig. 1. Symbol of a fluidic flip-flop and its truth table

<table>
<thead>
<tr>
<th>Cl</th>
<th>C2</th>
<th>01</th>
<th>02</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0</td>
<td>1 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 0</td>
<td>0 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 0</td>
<td>0 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 1</td>
<td>1 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 0</td>
<td>1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Simple design representation of a flip-flop
Fig. 3. Natural jet spread and vortice formation

Fig. 4. Wall attachment to an adjacent wall
FLOW OUT OF 01, NO CONTROL

FLOW OUT OF 02, NO CONTROL

CONTROL C1 IS ACTIVE
FLOW OUT OF 02

CONTROL C2 IS ACTIVE
FLOW OUT OF 01

Fig. 5. Sequence of controls and outputs used in producing truth table
The experimental study consisted of gathering enough information to produce a wall attachment device capable of controlling particle flow. It was necessary to carry out the study in several steps. The information gathered in the early analyses was needed to produce the design of the experimental apparatus for the subsequent study.

The first step was to verify that wall attachment could be induced using a large nozzle and relatively high pressure. The first piece of experimental apparatus was constructed from plywood and consisted of a stationary right angle wall and a movable adjacent boundary wall as shown in Fig. 6. The model, with one stationary right angle wall and one movable wall, was then refined to include a nozzle, shown in Fig. 7. The information gathered was then used to produce a bistable device including controls, and in the final stages, vents. This device contains two stationary angled boundary walls (Fig. 8). The model was constructed from plexiglas to facilitate visual observations. Both the plywood model and plexiglas model were used to study wall attachment and also the parameters which influence moving particles in an attached jet stream. In the plywood model, pressurized air was used to produce the fluid jet. In the plexiglas model, both air and water were used to produce the jet.

Particles used in testing were round in shape in order to reduce the complexity of particle motion. Two types of particles referred to
in this paper are styrene pellets and plastic beads. The styrene pellets have an average weight of 0.008 grams while the plastic beads have an average weight of 0.261 grams. Both types of particles were near 0.3125 inches in diameter.

The last analysis was done with the plexiglas model and simple moving parts. This was done to produce an improvement in the device's performance without reducing its reliability.
**Figure 6.** Large scale plywood wall attachment device

Large scale plywood wall attachment device.
Fig. 7. Large scale plywood model with converging nozzle
SPLITTER

Fig. 8. Plexiglas model with fixed walls and controls
CHAPTER III

DETERMINATION OF WALL ATTACHMENT AND WALL ANGLE

I. INTRODUCTION

The initial experimental investigation was undertaken to ascertain the feasibility of constructing a large scale wall attachment device which will be capable of controlling particle flow. The immediate area of interest was to produce a device which would induce wall attachment.

II. METHODS AND MATERIALS

The apparatus used in this investigation consisted basically of a four foot by four foot piece of 1/2 inch A.D. interior plywood, catch bins, screen, glass, air supply, a fixed wall and a movable wall (Fig. 9).

The four foot by four foot plywood acted as a base upon which the device was constructed. The fixed wall and movable wall were mounted in such a manner as to form a non-converging nozzle. At a one foot radius from the movable joint, catch bins were constructed every five degrees in relation to the straight line of the movable wall as indicated in Fig. 9.

The outer edge of the catch bins, was covered with a fine screen which permitted the passage of air, but not of particles. A glass plate was used as a cover for the catch bins and plywood nozzle. This allowed visual observation while restricting the flow in the vertical direction.

The air supply tube was made of two inch plastic drainpipe with a 1/8 tee in the center. The particles were introduced through the tee. The tubing fits into the outer end of the plywood nozzle.
The movable wall was made of plywood with a flexible joint. It was held rigid to the base and parallel to the fixed wall up to the flexible joint, which allowed the one foot movable wall section to swing freely through various angles. Wall attachment took place along the one foot movable wall section as illustrated by Fig. 10.

The catch bins were numbered in such a manner as to be readily converted into degrees. For example: 1 indicates 5 degrees left of the movable wall straight line, 2 indicates 10 degrees to the left, -2 indicates 10 degrees to the right of the straight line.

After constructing the described device, a method of determining its ability to induce wall attachment was formulated. This consisted of dusting the output region with fine particles, sawdust, which were easily moved by the air stream and readily visible.

The movable wall was adjusted in steps of five degrees from a zero degree angle to a sixty degree angle. At each position the output region was dusted and the air turned on. Readings were taken at the upstream edge of the catch bins, and the extreme outer bins where particles had been removed was recorded as depicted in Fig. 10.

III. EXPERIMENTAL RESULTS

The experiment was performed as described. The results are in Table I. As indicated in the table, 45 degrees was the last point of wall influence and 30 degrees was the last point of wall attachment. Natural jet spread at a distance of one foot was 20 degrees, indicated by the last three readings in Table I. The 25 degree spread was caused by a releasing of wall attachment but not of wall influence.
IV. CONCLUSIONS

The results of the experiment indicate that it was possible to induce wall attachment in a large model; however, the wall attachment seemed to be weak as shown by the large angle of jet spread. This indicated a need to increase the pressure drop across the jet stream.
Fig. 9. Experimental plywood model
TABLE I

JET SPREAD FOR NON-CONVERGING NOZZLE
AT ADJUSTED ATTACHMENT WALL ANGLES

<table>
<thead>
<tr>
<th>ANGLE OF ATTACHMENT WALL (DEGREES)</th>
<th>EXTREME CATCH BINS WHERE PARTICLES WERE REMOVED</th>
<th>SPREAD OF JET (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1 - -3</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>1 - -2</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>2 - -2</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>3 - -1</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>4 -  1</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>5 -  2</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>6 -  2</td>
<td>25</td>
</tr>
<tr>
<td>35</td>
<td>6.5 - 2.5</td>
<td>25</td>
</tr>
<tr>
<td>40</td>
<td>4 - -1</td>
<td>25</td>
</tr>
<tr>
<td>45</td>
<td>3 - -1</td>
<td>20</td>
</tr>
<tr>
<td>50</td>
<td>2 - -2 Centered</td>
<td>20</td>
</tr>
<tr>
<td>55</td>
<td>2 - -2</td>
<td>20</td>
</tr>
<tr>
<td>60</td>
<td>2 - -2</td>
<td>20</td>
</tr>
</tbody>
</table>

Output was dusted to indicate stream flow; and the extreme catch bins where particles had been removed was recorded as shown in Fig. 10.
PARTICLES HAVE BEEN REMOVED FROM BINS 4 TO 2 REPRESENTING A SPREAD OF 15 DEGREES

Fig. 10. Example of dusted track experiment
CHAPTER IV

DETERMINATION OF NOZZLE EFFECT ON WALL ATTACHMENT

I. INTRODUCTION

With consideration of the conclusions of Chapter III, the model was changed to include a converging nozzle. This increased the velocity of the fluid jet immediately before confronting the boundary wall as shown in Fig. 11. This study was again concerned with wall attachment, and also included an analysis of particle behavior in the following areas:

1. The ability of a fluid jet to attach to a wall while carrying particles.

2. Distribution of the particles being carried by the attached jet, at some point downstream of the attachment point.

II. METHODS AND MATERIALS

The apparatus used is the same as described in Chapter III; however, a convergent nozzle has been added as indicated in Fig. 11. Figures 12 and 13 show the refined model.

The first experiment was identical to the one run for a non-converging nozzle with the movable wall being placed every five degrees from 0 degrees to 30 degrees. The track was dusted as before and the results were recorded.

The second part included a study of the statistical distribution of the particle recovery. The particles used were styrene pellets. Twenty pellets were introduced separately, approximately one every second.
The movable wall was set at 0 degree and advanced to 30 degrees in steps of five degrees. At each position six runs were made. Of the six runs, three were made, each with 20 pellets, at one flow rate; the other three were conducted at a higher flow rate. The particles were collected in the catch bins; the number of particles in each of the bins was recorded.

III. EXPERIMENTAL RESULTS

Performing the experiment with the convergent nozzle, yielded results shown in Table II. These results indicate the jet spread as was shown by dusting the track. As concluded in Chapter III, greater wall attachment was realized by increasing the velocity of the jet. The jet spread was reduced to 12.5 degrees and was maintained at this value up to a wall deflection of 30 degrees. At the larger deflection angles, a larger air flow was used to obtain greater wall attachment. The natural spread at a distance of one foot from the nozzle was approximately 20 degrees. It was visually possible to detect the highest jet velocities near the attachment wall. See the velocity gradient in Fig. 4.

Because wall attachment is constant and easily obtainable up to a wall deflection of 30 degrees, the sequence involving particle flow will be run for wall deflections only up to 30 degrees. The results of the described experiment are shown in Table III. A graph relating the results of a non-converging nozzle and a converging nozzle are shown in Fig. 14.

The greater the angle of the attachment wall, the less likely the recovery of particles near the wall. This is revealed by a 71.66 percent recovery of particles twenty degrees from the wall at a wall angle.
setting of 20 degrees, as compared to 40 percent recovery of particles at 20 degrees with a wall angle setting of 30 degrees.

The construction of the attachment wall differs from most commercial designs in that there is no off-set as is indicated in Fig. 15. This rounding of the attachment corner reduces the separation bubble usually associated with wall attachment. Visual observation could not detect a separation bubble in the rounded model. This helps prevent circulation of the particles in that region.

It was observed that there was an exchange of momentum between particles and also between particles and the walls of the device. The most obvious effect was that of particles bouncing off of a wall at the nozzle and attaining large perpendicular angles relative to the jet stream flow. As shown in Fig. 16, this bouncing action caused the particles to become uncontrolled; in that they did not follow the directional change of the attached jet stream.

IV. CONCLUSIONS

Referring to the experimental results, it can be concluded that an increase in velocity can cause an increase in wall attachment. It is also clear that it is possible to control the direction of a particle by entraining it within a jet stream which is under the influence of wall attachment. It is evident that several design considerations must be met in order to produce an efficient model. The most prevalent ones are:

1. The need for sufficient velocities to obtain strong wall attachment.

2. The need to reduce sharp corners to diminish particle interaction with boundary walls and vortex flow.
3. The need for an extended nozzle capable of reducing particle bounce.

4. The need for wall attachment angles large enough to give discernible directional changes of entrained particles, but not so large as to reduce wall attachment or allow the inertia of the particle to break it free from the control force of the attached jet.
EACH BIN IS 5 DEGREES

STRAIGHT LINE

BINS 3 AND 4 WOULD REPRESENT A 10 DEGREE RECOVERY AREA

FIXED WALL

NOZZLE

SUPPLY

Fig. 11. Model of converging nozzle and recovery area definition
Fig. 12. Plywood model with converging nozzle

Fig. 13. Complete experimental plywood apparatus
### TABLE II

**JET SPREAD FOR CONVERGING NOZZLE AT ADJUSTED ATTACHMENT WALL ANGLES**

<table>
<thead>
<tr>
<th>ANGLE OF ATTACHMENT WALL (DEGREES)</th>
<th>EXTREME CATCH BINS WHERE PARTICLES WERE REMOVED</th>
<th>SPREAD OF JET (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1 – -2.5</td>
<td>12.5</td>
</tr>
<tr>
<td>5</td>
<td>1 – -1.5</td>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
<td>2 – 1.5</td>
<td>12.5</td>
</tr>
<tr>
<td>15</td>
<td>3 – 2.5</td>
<td>12.5</td>
</tr>
<tr>
<td>20</td>
<td>4 – 3.5</td>
<td>12.5</td>
</tr>
<tr>
<td>25</td>
<td>5 – 4.5</td>
<td>12.5</td>
</tr>
<tr>
<td>30</td>
<td>6 – 5.5</td>
<td>12.5</td>
</tr>
<tr>
<td>35</td>
<td>*7 – 6.5</td>
<td>12.5</td>
</tr>
<tr>
<td>40</td>
<td>3 – -2</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>*8 – 6</td>
<td>15</td>
</tr>
<tr>
<td>45</td>
<td>2 – -2 Centered</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>*9 – 7</td>
<td>15</td>
</tr>
<tr>
<td>50</td>
<td>2 – -2 Centered</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>*3 – -2.5</td>
<td>27.5</td>
</tr>
<tr>
<td>55</td>
<td>2 – -2 Centered</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>*3 – -2.5</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Output was dusted to indicate stream flow; and the extreme catch bins where particles had been removed was recorded as shown in Fig. 10.

* Initially not completely attached but became attached with an increase in the air flow.
Fig. 14. Wall attachment verses wall angle for converging and non-converging nozzle
<table>
<thead>
<tr>
<th>ANGLE OF ATTACHMENT WALL (DEGREES)</th>
<th>FLOW RATE</th>
<th>PERCENT RECOVERY IN DEGREES FROM THE ATTACHMENT WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(10)</td>
</tr>
<tr>
<td>0</td>
<td>A</td>
<td>80.33</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>83.33</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>66.66</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>58.33</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
<td>51.66</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>A</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>35</td>
</tr>
<tr>
<td>20</td>
<td>A</td>
<td>31.66</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>38.33</td>
</tr>
<tr>
<td>25</td>
<td>A</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>36.66</td>
</tr>
<tr>
<td>30</td>
<td>A</td>
<td>26.66</td>
</tr>
</tbody>
</table>

A= 1 and 1/2 turns of the air valve  
B= 2 turns of the air valve
Fig. 15. Curved wall and off-set wall
Fig. 16. Example of particle interaction with wall
CHAPTER V

TESTING A BISTABLE WALL ATTACHMENT DEVICE

I. INTRODUCTION

Relying on the data assembled in the earlier analysis it was possible to construct a bistable device. With this device, experiments of optimum splitter position and overall device performance characteristics were carried out. The following aspects of wall attachment and particle control were investigated:

1. The ability of the device to produce wall attachment and to respond to switching
2. The optimum location of the splitter
3. The relation of particle density and particle size to device performance.

II. METHODS AND MATERIALS

The bistable device was constructed of clear plexiglas plate because it is easily machinable and can allow visual observation of particle action. The device was reduced in size from the plywood model. This size reduction made it more convenient to handle and also to obtain higher velocities with the fixed air supply. The physical dimensions of the device are given in Appendix A.

The model consisted of a nozzle which contains rounded corners and two fixed angled attachment walls; again, rounded corners were used to
reduce the size of the separation bubble. As indicated in Fig. 17, there were two control ports which lie perpendicular to the nozzle and enter just before the nozzle exit. Figures 18 and 19 show that the small nozzle section was extended in length to lessen particle bounce as noted in Chapter IV.

The jet stream was produced by sending pressurized air through an expanding nozzle. This nozzle contained holes to allow air to be entrained, thus increasing the total air flow. A tee was placed directly after the nozzle, through which particles were introduced into the stream (Fig. 20). Following the tee was a long pipe section which helped to stabilize the particle flow before it entered the attachment device. Converting the round supply tube to the rectangular device nozzle was accomplished with the use of an adapter. It was designed in such a manner that the inside diameter of the pipe was reduced through a short nozzle. The reduced diameter, as shown in Fig. 20, was inscribed within the rectangular section; therefore, there were no sharp corners.

The nozzle of the plexiglas model was constructed with a square section reducing to a rectangular section which had approximately one half the area of the square section. This area reduction was utilized to act as a venturi meter by drilling pressure taps into the channel. These taps were connected to a differential water manometer, thus making it possible to reproduce a given air velocity and to calculate the total air flow from the Bernoulli equation, as in Appendix B.

Once the splitter had been placed, the device had essentially two outputs. The device performance was measured by the percentage of recovery of particles at the output in which the flow was active. It was therefore necessary to collect the particles from each output. This was achieved
by use of cyclone bins. Fig. 27 indicates how the bins allowed for the escape of air but not of particles, which rotated around inside the bin.

After the model was assembled, the testing was begun. The first test was that of wall attachment. This was carried out without a splitter and only a visual evaluation of the outcome. Paper strips were attached near the outer walls of the model to indicate if there was air flow when the jet was applied. The controls were tested to determine if the attached jet would separate and attach to the opposite wall and whether it would remain attached even after the control was removed. No evaluation of control flow to separation time was made.

The next test was performed to determine an optimum splitter location. The criteria used for determining optimization was based on the achievement of the highest efficiency in recovery of particles. The particles used were styrene pellets. The styrene pellets were light and could be easily entrained by the jet, thus requiring less force to turn the corner.

The splitter was set in various positions beginning near the mean line (the mean line is the center line of the controls as shown in Fig. 17) and moved farther away after each test run. A test run consisted of twelve sets of fifty pellets introduced several at a time into the air stream. The twelve sets were broken into four subsets; three sets at one velocity out of output 01, and three out of output 02 at the same velocity. After the velocity was increased another three sets were run for 01 and three for 02. After each set, a recording was made of the number of pellets received by the active output and passive output. The splitter was moved from 1.25 inches away from the mean line, to a distance of 2.1875 inches from the mean line.
After evaluating the results of the above test, the splitter was fixed in the optimum position for maximum recovery. With the splitter fixed, another set of tests was conducted. This time the plastic beads were used as particles. The jet velocity was now made variable and six sets were run at one velocity; three at 01, and three at 02. The velocity was increased from the lowest velocity capable of producing wall attachment, to the highest velocity capable of being produced by the system, the latter was 8 inches pressure differential on the water manometer.

III. EXPERIMENTAL RESULTS

The first test was carried out as previously described. By applying the main jet, wall attachment was readily achieved. It was also shown that flow from the correct control would move the main jet from one wall to the other wall where it would attach. The control pressure needed to cause switching was high. This indicated a low pressure gain but a relatively high flow gain.

The second test involved the position of the splitter. The method has been described and the results are given in graph form. The first graph on Fig. 22, gives the percent recovery verses the splitter position with a high flow rate (a differential manometer reading of 6.5 inches of water) for output 01 and 02. Fig. 23 gives the same results but for the lower flow rate of 3.25 inches pressure differential. The third graph, Fig. 24, combines the averages of the first two tests to give the average device performance. After analyzing the data gathered in the above test, a splitter position of two inches from the mean line was chosen for the remainder of this study.
The third test was conducted to help analyze the importance of the jet velocity to the percentage of particles recovered. Fig. 25 gives the relationship between the particle recovery and the pressure differential. The largest pressure differential was 8 inches. A pressure differential of 2 inches was the lower limit; below that, uncontrolled switching was observed.

As described, the outputs were open to the air. This allowed air to be drawn up the passive output because of the air entrainment of the jet. Particles which entered the incorrect output were often returned to the jet because of this reverse flow. As shown in Fig. 26, the flow seems to be strongest against the splitter, and particles passing near the wall were not often returned to the active output. This returning of particles was not prevalent when transporting heavier particles, because their forward momentum carried them through the reverse flow.

IV. CONCLUSIONS

The results of the first test indicate that the device was capable not only of obtaining wall attachment, but, also of being able to respond to controls.

The graphical results of the second test as in Figures 22, 23, and 24 have several interesting points. One obvious conclusion was that because of the physical arrangement, the device was biased to a higher recovery at output 01, at both the high and low velocities. A second point of interest was the seeming valley and peak configuration of particle recovery to splitter position. This same observation on pressure recovery was recorded in a paper by K. Foster and N. S. Jones.
although no explanation was given. It may be possible that the peaking was caused by the stabilized vortex location. At a steady flow the vortices become fixed in position. If the splitter was in such a position as to be located just at the bottom of a vortex, then the outward flow of the vortex would restrict the entrainment of air and a drop in wall attachment and particle recovery would occur. If however, the position of the splitter was at the top of a vortex, the air entrainment would be enhanced; thus, producing better wall attachment and greater particle recovery (Fig. 27). This conclusion takes into account the difference in location of the peaks between high and low velocity. The low velocity jet had vortices which stabilized at different locations than the vortices of the high velocity jet.

Concerning oneself with the total performance of the device, it was recognized that a splitter position of two inches from the mean line was the only point where both the high and the low velocities, and both outputs, are nearly equal in recovery. This made two inches the position of highest overall recovery efficiency.

Comparing the results of the recovery of the styrene pellets at a pressure differential of 6.5 inches and splitter position of two inches with the plastic beads at the same pressure differential and splitter position, a 93 percent recovery verses a 58.66 percent recovery was found. Realizing that the only difference in the results was the density of the particles, it can be concluded that particle momentum plays an important role in determining how effectively particles can be controlled by an attached jet. As mentioned, the momentum also prevented the beads from being forced back into the jet by the reversed
flow in the passive output.

It was difficult to determine which is more important; a high velocity for greater particle entrainment and greater wall attachment, or a low velocity for smaller particle momentum. An insight can be found in Fig. 25. At lower velocities, a relatively high recovery was indicated. As the velocity increases, the momentum of the particle overcomes the particle entrainment, producing relatively low recovery. However, as the velocity increases to a higher value, the wall attachment and particle entrainment overcome the momentum and an increase in recovery can be realized.

From the results, one can conclude that vents should be added to the device. This would increase the cross flow of air as it is entrained into the jet stream. It would make the device load insensitive; in that the output could be blocked and no uncontrolled switching would take place. It would also be necessary to have vents if the device is to be incorporated into a closed system; because otherwise there will be no air available for entrainment.
Fig. 17. Location of splitter
Fig. 18. Device showing splitter and controls

Fig. 19. Cyclone bins used to catch particles
PARTICLES MAY BE INTRODUCED HERE

HIGH PRESSURE AIR

HOLES

TO THE DEVICE

ONE INCH I.D. PIPE

REDUCING NOZZLE DEVICE

\[ D1 \quad W1 \]

Fig. 20. Air supply and adapter for plexiglas model
Fig. 21. Cyclone bin used to catch the particles from the output.
Fig. 22. Splitter distance versus particle recovery
Fig. 23. Splitter distance verses particle recovery

- OUTPUT 01
- OUTPUT 02

PRESSURE DIFFERENTIAL
OF 3.25"
STYRENE PELLETS
Fig. 24. Splitter distance versus average particle recovery

- □ 6.5 INCHES
- △ 3.25 INCHES

STYRENE PELLETS

SPLITTER DISTANCE FROM MEAN LINE IN INCHES

PERCENT RECOVERY
Fig. 25. Pressure differential verses recovery efficiency
Fig. 26. Reverse flow in the passive output caused by air entrainment
Fig. 27. Splitter location and vortex action
CHAPTER VI

TESTING A VENTED WALL ATTACHMENT DEVICE

I. INTRODUCTION

The main emphasis here was on the effect of vents on the recovery efficiency of the device as compared to the results gathered before the vents were added. Note in Fig. 28 the angle the vent forms with the attachment wall; this reduces the possibility of particles becoming lodged in the vent.

II. METHODS AND MATERIALS

The same device was used as before except for the addition of the vents. The vents are 0.1875 inches in diameter and form a 75 degree angle with the boundary wall. They enter into the output leg 0.0375 inches downstream from the splitter apex (Fig. 28). The test device was arranged as in Chapter V, and testings were carried out with a set splitter location of two inches from the mean line. Plastic beads were sent through the device at five different pressures. The testing was the same as described in Chapter V for velocity variations.

III. EXPERIMENTAL RESULTS

After arranging the device for testing, it was found that the vents were not capable of making the model load insensitive. If flow was coming from output 01 and this output was blocked, the flow was
switched to output 02. Even though the vents did not make the device insensitive to loading, no alteration was made in the vents before testing was undertaken. The results are plotted on Fig. 29.

IV. CONCLUSIONS

Because the testing of the effect of velocity on particles recovered corresponded exactly to that in Chapter V except for the addition of the vents, comparison of the results was possible. As noted, the vented device was erratic in the lower flow regions; however, it is significant to note the steeper slope associated with connecting the last two plotted points. It is indicated that higher recoveries can be obtained with higher flow rates. This is an indication of greater wall attachment as well as increased lateral flow from the vent to the entrainment jet.

The device is now a complete element, capable of transporting particles as well as specifying flow direction between two possible outputs.
VENT

A = 0.375"
B = 15 degrees

Fig. 28. Vented device
Fig. 29. Pressure differential versus recovery efficiency
CHAPTER VII

PERFORMANCE OF THE BISTABLE DEVICE USING A WATER JET

I. INTRODUCTION

This section was included to test the performance of the bistable device using water and the influence of water on the recovery efficiency of particles by this device. No quantitative measurement was made of the flow rate of water through the device; however, it was much lower than the flow rate of the air jet.

II. METHODS AND MATERIALS

The device used in this study was the same as described in Chapter V, and did not contain vents. The air supply was replaced by a water supply. The testing included a visual observation of wall attachment as well as the ability of the device to detach and reattach to the opposite output. The recovery testing was done using plastic beads, introduced as before, several feet upstream from the nozzle.

III. EXPERIMENTAL RESULTS

When testing the device in air, it was found that the attached water jet could not maintain the vertical wall necessary for flow attachment. This caused the jet stream to collapse into the lower half of the output legs and divide fairly equally between each output. By submerging the device in water, it was found that the device could obtain a stable wall attachment and also be switched and reattached to
the opposite output.

Introduction of particles was also done under water, thus eliminating air bubbles which could cause the device to perform poorly. It was found that 100 percent particle control was obtained when using a water jet. This can be roughly compared to a high 50 percent recovery range for the same particles using an air jet.

IV. CONCLUSIONS

From these tests, two conclusions can be drawn. The first is that it is possible to obtain wall attachment by using water. This opens avenues for possible application of the device for slurry control. The second conclusion is that water, which has a higher density and viscosity than air, has a greater influence on particles than air.
CHAPTER VIII

MAKING A BISTABLE DEVICE MORE EFFICIENT FOR PARTICLE FLOW CONTROL

I. INTRODUCTION

The device developed at this point cannot attain 100 percent particle recovery at the specified output using an air stream for the working fluid. In industrial applications it may be necessary to have complete control of the particle flow; therefore, three possible alterations of the device were developed to increase the collection efficiency of the device.

II. METHODS AND MATERIALS

The three designs include additional features on the device, but do not destroy the geometry of the device. The designs were referred to as:

1. Lifted leg
2. Blocked vane
3. Guiding vane

The names are indicative of the structural design of the additional features.

The lifted leg device was a momentum reducing arrangement which was incorporated into the output of the device. The addition of an elevated leg at the upper end of the output, as in Fig. 30, accounts for the name.
The function of this device was to create a potential jump over which the particle must pass. There are two situations at which the particles encountered the lifted leg. One was when a particle entered the inactive leg, and, the other was when a particle entered the active leg. Since there was flow in the active leg, the particle had both its momentum and the force of the jet flow available to overcome the rise in potential imposed by the jump. The particle which entered the inactive output had only its momentum. Therefore, by designing the legs to the correct height, the momentum of the particle was unable to raise the particle over the jump. Thus, the device would transport only the particles which had entered the correct leg.

The blocking vane design incorporated the use of a moving part and thus removed the device from the region of pure fluidics; however, the moving part only directed particles and did not affect the control characteristics of the device. The blocking vane was very simple in design and had only one pivot point; thus it did not introduce any serious operating problems.

Basically, the blocking vane was used to block the particles which have entered the inactive output. The vane, as shown in Fig. 31, was situated such that it pivoted at the apex of the splitter. Flow through an output forces the side of the blocking vane in that output to rest against the splitter wall. Because of the geometry of the vane, the opposite side of the vane is moved to block the inactive output. When particles entered the inactive leg, they were stopped by the blocking vane. The vane was designed so that it did not interfere with air flow through the vents which was caused by the jet entrainment. This entrainment flow helped to return particles to the active output.
The guiding vane device used two moving parts of the simplest form. The guiding vanes were located at the sides of the nozzle and were pivoted upstream from the control ports to guide particles into the correct output. Flow in an output caused one vane to be pressed against the boundary wall of that output and the other vane to deflect toward the active output. Therefore, particles were guided to the specified active output. Fig. 32 shows that the forces holding the deflector vane in position were created by the pressure differential caused by the fluid stream and the reverse flow in the inactive leg.

III. EXPERIMENTAL RESULTS

Testing of the devices indicated that 100 percent of the particles recovered could be obtained at the appropriate output. This was true only when the devices were correctly applied.

In the lifted leg device, particles which entered the inactive output which were not re-entrained or bounced back into the stream did remain in the inactive output leg. When the flow was switched, the particles which had settled in the previously inactive output were forced by the air stream to go over the jump. For non-horizontal applications, variations in the lifted leg design would be necessary to achieve the same high performance.

Particles being transported in the blocking vane design sometimes caused an uncontrolled switching to occur. This was prevalent when heavy particles with high momentums struck the blocking vane, or when a number of particles collided on the blocking vane at one time. Particles which entered the inactive leg, either bounced back into the active stream, or were carried back by the air flow in the vent.
No particles remained in the inactive output in this case.

The guiding vane device did not undergo uncontrolled switching. Because of the guiding vane action, flow of large concentrations and heavy particles could be controlled by the device. The major problem was that of switching.

IV. CONCLUSIONS

Under controlled operating conditions, all designs achieved 100 percent recovery of particles at the correct output except in the lifted leg design where some particles settled in the inactive leg.

The lifted leg design was capable of transporting fairly uniform particles. If the device is used to transport several particles at one time, the difference in momentum due to different masses may cause the device to perform poorly. Even if particles being transported at any one time are uniform, the height of the jump will be dependent of their momentum and directly related to the gas velocity. When changing to a different particle, the leg height would have to be adjusted.

The blocking vane device can handle a mixture of particles. If, however, the loading of the air stream with particles should be too heavy, uncontrolled switching will occur.

The guiding vane design, can handle the greatest variation in particles, loading conditions, and velocities. This design would most likely require higher switching pressures.

It is concluded that through design manipulation, a high recovery device can be developed. The addition of a simple moving part should not
introduce serious maintenance problems.
Fig. 30. Lifted leg device
Fig. 31. Blocking vane device
Fig. 32. Guiding vane device
CHAPTER IX

SUMMARY AND CONCLUSION

The experimental results indicate that the Coanda effect can be used to control the directional flow of particles. There were no substantial problems in developing a large scale device which could obtain wall attachment and also be controlled as in a Flip-Flop. The major difficulties arose from using the attached jet to control the flow of particles.

There are many parameters which influence particle flow in a fluid stream; they include: particle area, particle density, particle shape, fluid density, fluid velocity, and fluid viscosity. These parameters are related to primary forces, such as: particle lift, longitudinal drag, fluid velocity gradient, particle momentum, transverse drag and fluid momentum.

The development of the plexiglas device minimized those forces which dominate the fluid influence on the particle and maximized the forces affecting the wall attachment of the fluid stream. In most instances, the two aims were opposed to each other. Compromises were made so that the device could perform both as a Flip-Flop and as a diverting valve.

The velocity of the fluid jet increased both the wall attachment and the lifting forces on the particle. It also increased the particles inertial forces, which adversely effect the directional control.
The mass of the particles being transported is related to the volume of the particle and their density. The greater the particle area, the larger the drag force. The higher the density for a given volume, the larger the inertial forces on the particles.

One area which produced positive effects on wall attachment was the use of fluids with high density and viscosity. However, in application this has practical disadvantages.

Assuming that there was no control on the type of particle being transported or the fluid being used as the working fluid, a summary of design characteristics would include:

1. Making the device physically large enough to transport a specific particle
2. Reducing obstructions which would hinder particle flow or be subject to erosion
3. Inducing good wall attachment of the fluid flow
4. Increasing the gain of the device without adversely affecting particle control.

The step by step experimental development of the finalplexiglas model gives insight into some methods of achieving the goal of using wall attachment to directionally control particle flow.

The use of lifted output legs or simple moving parts, brings the device into the realm of realistic application in industrial processes. It would be possible to construct transporting circuits utilizing several elements to control particle flow to more than two outputs. Control logic could consist completely of fluid devices and thus provide safe reliable operation within a given system.
REFERENCES


REFERENCES NOT CITED


**APPENDIX A**

**DIMENSIONS FOR THE PLEXIGLAS DEVICE**

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Device</strong></td>
<td>10.25&quot; long, 4&quot; wide, 1.5&quot; high</td>
</tr>
<tr>
<td><strong>Nozzle</strong></td>
<td>1&quot; wide, 1&quot; high</td>
</tr>
<tr>
<td><strong>Throat</strong></td>
<td>2.75&quot; long, 0.5&quot; wide, 1&quot; high</td>
</tr>
<tr>
<td><strong>Boundary wall angle</strong></td>
<td>18 degrees from center line</td>
</tr>
<tr>
<td><strong>Splitter</strong></td>
<td>18 degrees from center line</td>
</tr>
<tr>
<td><strong>Controls</strong></td>
<td>0.1875&quot; in diameter, enter at exit of nozzle</td>
</tr>
<tr>
<td><strong>Vents</strong></td>
<td>0.1875&quot; in diameter, enter 0.375&quot; downstream from the splitter apex, form a 75 degree angle with boundary walls</td>
</tr>
<tr>
<td><strong>Output legs</strong></td>
<td>1&quot; high, 1&quot; wide</td>
</tr>
</tbody>
</table>
APPENDIX B

FLOW RATE AND VELOCITY AS RELATED TO PRESSURE DIFFERENTIAL

The Bernoulli equation was used to calculate the flow rate and velocity through the plexiglas device for the pressure differentials given below.

<table>
<thead>
<tr>
<th>PRESSURE DIFFERENTIAL</th>
<th>VELOCITY IN THE THROAT SECTION</th>
<th>FLOW RATE IN CUBIC FT PER MIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN INCHES WATER</td>
<td>FT PER SEC</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>108</td>
<td>21.1</td>
</tr>
<tr>
<td>3.25</td>
<td>137.5</td>
<td>26.9</td>
</tr>
<tr>
<td>4.5</td>
<td>162</td>
<td>31.7</td>
</tr>
<tr>
<td>6.5</td>
<td>194.5</td>
<td>38.0</td>
</tr>
<tr>
<td>8</td>
<td>216</td>
<td>42.3</td>
</tr>
</tbody>
</table>