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PILOT-PLANT TESTING OF A TWO-PHASE VORTEX FLUID
AMPLIFIER FOR LIQUID FLOW CONTROL

IDAHO NUCLEAR CORPORATION
NATIONAL REACTOR TESTING STATION
IDAHO FALLS, IDAHO

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PILOT-PLANT TESTING OF A TWO-PHASE VORTEX
FLUID AMPLIFIER FOR LIQUID FLOW CONTROL

By

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ABSTRACT

Pilot-plant tests were conducted to evaluate a vortex restrictor for use as a substitute flow control device in a radioactive slurry feed system in which mechanical control valves have been plugged by suspended solids. The restrictor was operated satisfactorily for 1169 hours using a mock-up of the Waste Calcining Facility feed system; successful flow control was obtained without failure due to plugging or erosion in the restrictor. Air was used to regulate the flow rate and to avoid any dilution of the slurry. This device performed at least as well as the more expensive mechanical valve in the particular application for which it was tested.

SUMMARY

Suspended solids in the radioactive liquid waste fed to the fluidized-bed calciner in the Waste Calcining Facility (WCF) at the Idaho Chemical Processing Plant (ICPP) have occasionally plugged the mechanical flow control valves. A stainless steel vortex restrictor, patterned after a vortex fluid amplifier, was tested as a possible substitute flow control device in a mock-up of the WCF feed system. Air was used as the controlling fluid in the vortex restrictor to avoid dilution of the liquid feed; this is an unusual method of operation since both controlled and controlling streams in a fluidic unit are normally the same phase. The pressure drop across the restrictor, measured from the liquid inlet to the two-phase outlet, was found to be a strong function of liquid and control-air flow rates.

Using an acidic slurry chemically similar to radioactive zirconium waste, the vortex restrictor was operated for 1169 hours at a nominal flow rate of 30 gph in a full scale mock-up of the WCF feed system. This test showed that use of a vortex restrictor results in: (1) reliable control of the calciner feed rate in the range 10-110 gph without process stream dilution, (2) operation for extended periods without plugging or flow rate upset, even with open-loop control, and (3) no deposition of dried solids in the restrictor or downstream piping. The test results indicate that this less expensive vortex restrictor would perform at least as well as a mechanical control valve in the WCF feed system.

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I. INTRODUCTION

The Waste Calcining Facility (WCF) at the Idaho Chemical Processing Plant (ICPP) calcines radioactive aluminum and zirconium liquid waste generated during the processing of spent nuclear fuel elements. The liquid is fed by gravity from a constant head tank to a hot fluidized bed as shown in the schematic flowsheet in Figure 1. The flow of feed to each nozzle, at a nominal rate of 30 gph, is presently controlled by a pneumatically operated bellows-sealed valve⁽¹⁾. Suspended solids in the liquid waste feed have occasionally plugged the valves and restricted the flow of solution to the calcining vessel⁽²⁾. Since any equipment used in radioactive service must be as reliable as possible, a pilot-plant study of flow control using a mechanically simpler vortex fluid amplifier as a vortex restrictor was initiated.

Figure 1
Schematic Flowsheet of WCF Feed System

Figure 2
Stainless Steel Vortex Restrictor

A fluid amplifier is a device designed to permit flow control of a main fluid stream by a relatively small change in the flow of a control fluid. The device contains no moving parts; control is achieved when either the control fluid causes a portion of the main fluid to be diverted, or the control fluid restricts the flow of the main fluid(3,4).

The vortex restrictor used in the pilot-plant tests consisted of the three mating pieces, made from Type 304 stainless steel, shown in Figure 2. When bolted together the pieces formed a shallow, one-inch diameter by one-half inch high, cylindrical chamber. The chamber dimensions were similar to a commercial vortex fluid amplifier because no design data were available for a two-phase vortex restrictor. The liquid entered radially through a 5/16 by 1/2-inch rectangular port in the wall of the chamber; the control-air entered tangentially through two 1/16-inch orifices in the cylinder wall. The two-phase mixture flowed axially out of the chamber through a 1/4-inch orifice as shown in Figure 3. By increasing the control stream flow rate, the pressure drop across the vortex was increased due to the friction loss resulting from the angular and radial accelerations of the fluids; the pressure drop impedes the flow of liquid through the chamber.

Figure 3
Flow Pattern in Vortex Restrictor

The vortex restrictor was selected for testing in preference to other types of fluidic units because:

1. The controlled liquid is restricted rather than diverted; this eliminates the need for recycling a stream of radioactive fluid.
2. Simple internal geometry makes plugging unlikely.
3. Air can be used as the control fluid for a liquid stream, thus avoiding dilution of the liquid.

The last advantage is unique to this particular flow control application; normally a vortex amplifier employs a control fluid of the same phase as the controlled fluid. Because the two fluids are mixed during operation, air was required as the control fluid to prevent dilution of the radioactive liquid and the resultant reduction in net feed rate to the calciner.

II. PILOT PLANT TEST

A. Pressure Drop Characteristics: The flow control capability of a vortex restrictor installed in a fluid system requires that the pressure drop across the restrictor be a significant fraction of the overall hydraulic head. Two-phase pressure drop data were obtained in scoping studies to determine applicability of the restrictor in the WCF feed system. The restrictor, with the cylinder axis in the vertical position and the outlet on the bottom, was tested in a simple apparatus using water as the controlled liquid. The pressure drop from the liquid inlet to the two-phase outlet was measured as a function of liquid and control-air flow rates.

The results indicate that the pressure drop across the restrictor is a nearly linear function of the control-air rate at constant liquid flow rates, as shown in Figure 4. However, an incremental change in control-air rate yields a greater change in pressure drop with increasing liquid flow rate. The overall head in the WCF feed system is over 7.0 psi; this pressure drop can be generated if 4.0 scfm of control air is added to the restrictor and if the liquid continues to flow at approximately 30 gph. Therefore, the restrictor could create enough pressure drop to significantly affect the flow. (An exact extrapolation of the data to WCF conditions was not possible because of the differences in fluid properties and because of additional impedance in the WCF feed system.)

The control-air was supplied to the restrictor through 1/4-inch pipes; the control-air flow rate was found to be nearly proportional to the supply pressure at constant liquid flow rates as shown in Figure 5. Sonic velocity is attained through an orifice whenever the critical pressure ratio is exceeded; the mass flow rate then becomes proportional to the supply pressure at that point. Under these conditions, the air injected the maximum possible angular momentum per unit mass into the vortex restrictor chamber. The minimum control-air pressure required to prevent liquid from backing into the air lines increases with increasing liquid flow rate as is also shown in Figure 5 by the intercept of the parametric curves with the abscissa. The upper end of

Figure 4
Pressure Drop Across Restrictor as a Function of Control-Air Flow Rate
(Water as the Controlled Fluid)

Figure 5
Control-Air Flow vs. Control-Air Pressure
(Water as the Controlled Fluid)

the curves terminated when the pressure drop across the restrictor reached 9.0 psi, the maximum measurable pressure drop in the apparatus.

At a constant air flow rate, a significant increase in pressure drop is measured when the liquid flow is stopped entirely as shown in Figure 6. This is thought to be the result of a drastic change in flow pattern in the transition from two-phase to single-phase flow. Under this condition, the pressure drop can easily exceed the available head of the WCF feed system.

Figure 6
Effect of Small Liquid Flow on Pressure Drop
(Water is the Controlled Fluid)

B. Vented and Non-Vented Operation: A vortex restrictor installed in the WCF feed system could be operated in two basic ways⁽⁵⁾. Air from the two-phase outlet stream could be disengaged below the restrictor, or the two-phase stream could be fed directly to the calciner feed nozzle. Figure 7 is a schematic flowsheet of the test apparatus showing both methods of operation. The overall head in the test system was the same as in the WCF feed system, and a full-scale calciner feed nozzle was employed in tests using water and aluminum nitrate solutions (> 2.0 M). Since a single feed nozzle in the WCF is designed to supply more than 90 gph if two of the three feed lines plug, the restrictor had to be capable of controlling flows from less than 30 gph to greater than 90 gph.

With vented operation, the two-phase mixture flowed through a 1/4-inch I.D. tube to a disengaging pot six inches below the vortex restrictor

Figure 7
Schematic Flowsheet of Apparatus for
Testing Vortex Restrictor Operating Mode

outlet. The restrictor was tested at a level equal to that at which the feed lines enter the calciner cell below the flowmeters. Satisfactory flow control was obtained at reasonable air rates (less than 4.0 scfm); however, the aluminum nitrate foamed in the disengaging pot where much of it flowed up the vent to the constant head tank rather than to the nozzle. Since the flow meter in this system and in the WCF feed system are positioned upstream from the flow control device, the flow to the nozzle could not be measured accurately using this method of operation.

Using the non-vented mode of operation, the two-phase mixture from the vortex restrictor flowed through a 1/2-inch pipe to the feed nozzle. When the pipe length from the restrictor to the nozzle contained several vertical and horizontal runs, the air and liquid tended to segregate into the slug flow regime. This made accurate flow control impossible because of the violent pressure oscillations associated with

slug flow. Qualitative observations revealed that less slugging resulted when shorter lengths of pipe were used; therefore, the vortex restrictor outlet was connected to the nozzle by only an 18-inch, long-radius elbow. This eliminated slugging and resulted in satisfactory control of water and aluminum nitrate solutions. The non-vented mode required no more control-air than the vented mode for a particular liquid flow rate, even though the head was greater, because of the simultaneous increase in pressure drop across the vortex restrictor and long-radius elbow when control-air is added.

C. Tests of Simulated WCF Feed System: A test loop for recycling an acidic slurry chemically similar to the radioactive zirconium waste fed to the WCF is shown in Figure 8; the composition of the slurry is shown in Table 1. The run of pipe from the constant head tank to the reservoir included the essential features of the WCF feed system: (1) equivalent gravity head, (2) butt-welded fittings and sloped pipe of equal diameter, (3) electromagnetic flowmeter or rotameter, and (4) WCF size spray nozzle. The nozzle was heated externally by electrical tapes to a temperature approximately that of the WCF (300°C on metal surface),

Figure 8
WCF Feed System Mock-up

and a vacuum was held on the reservoir to duplicate the pressure in the calciner. The piping layout of the long-radius elbow between the vortex restrictor and nozzle, shown in Figure 9, was compatible with the existing installation in the WCF(6).

TABLE 1
COMPOSITION OF SYNTHETIC ZIRCONIUM SLURRY WASTE

Total Solids	(g/l)	126.9
Aluminum	(g/l)	9.0
Zirconium	(g/l)	23.0
Calcium	(g/l)	37.2
Fluoride	(g/l)	30.6
Undissolved Solids	(g/l)	53.8
Zirconium	(w/o)	31.2
Calcium	(w/o)	14.1
Fluoride	(w/o)	31.2
Filtrate		
H ⁺	(<u>M</u>)	1.40
NO ₃ ⁻	(<u>M</u>)	3.80
Zr ⁺⁴	(<u>M</u>)	0.073
Al ⁺³	(<u>M</u>)	0.314
Ca ⁺⁺	(<u>M</u>)	0.74
F ⁻	(<u>M</u>)	0.74
Cr	(g/l)	0.396

The test loop was operated semi-continuously for a total of 1169 hours. Simulated zirconium fluoride waste slurry was circulated, and the batch was replaced every few days to maintain the acidity and corrosiveness of the solution. Aluminum nitrate solution was not used since satisfactory control was obtained in the non-vented test and the zirconium slurry contained a larger amount of suspended solids than the aluminum waste. Open-loop control was used with a rotameter for flow rate determinations (except when an electromagnetic flow meter was used to demonstrate automatic control); the control-air flow was adjusted manually. The liquid flow rate was maintained at 30 gph with a control-air rate of 2.0 scfm during most of the test; however, the liquid flow

Figure 9
Vortex Restrictor Installed in WCF Mock-up

Figure 10
Performance Curve for Vortex Restrictor
Operating in Mock-up of WCF Feed System
(Simulated Zirconium Feed)

could be controlled by proper selection of the control-air rate to any value between the maximum of 110 gph and a minimum of 10 gph.

A performance curve showing controlled liquid flow and pressure drop as a function of control-air flow is given in Figure 10. The liquid flow did not vary more than a few percent from a given value determined by the control-air rate.

The vortex restrictor was also tested as a final control element in a feedback control loop in which the liquid flow rate was sensed by an electromagnetic flowmeter as shown by the block diagram in Figure 11. The operation was unstable until a snubber was placed on the output line of the pneumatic recorder-controller. Satisfactory automatic control was demonstrated in the region of 30 gph; however, no optimization of the control parameters was attempted since the acidic slurry attacked the ceramic lining of the meter.

The vortex restrictor would also have to satisfy other requirements, in addition to its ability to successfully control the flow of liquid feed, to be suitable for the intended application:

1. Solids deposition caused by evaporation and drying of the two-phase mixture should not occur.
2. The rates of internal corrosion and erosion should be small.
3. The volume of control-air required should be small compared to the nozzle atomization air because the particle size of the fluidized bed is controlled by the nozzle atomization air.

Figure 11
Block Diagram of Vortex Restrictor
Feedback Control System

The apparatus was disassembled at the end of the test and inspected; no solids deposits were observed in the restrictor, pipe, or nozzle. The exact rates of corrosion and erosion in the restrictor chamber were too small to determine accurately. Although the inside surfaces were etched, there was no evidence of gross erosion near the orifices where air velocities are highest. The flow rate of the nozzle atomization air in the WCF varies from 25 to 35 scfm; the control-air rates of 0 to 4.0 scfm were comparatively small.

The temperature of the two-phase mixture, flowing at the nominal rate of 30 gph of liquid and 2.0 scfm of air, was 35°C as measured in the elbow above the nozzle body. When the flow of control-air to the system was stopped and the flow of liquid was maintained at 30 gph, the temperature rose 15 to 25°C higher at the same point. Thus, the air cooled the mixture entering the feed nozzle. This may prevent drying and excessive corrosion in the nozzle; however, the severe heating conditions found in the WCF could not be duplicated.

III. CONCLUSIONS

Results from pilot-plant tests using a vortex restrictor for control of calciner feed in a mock-up of the WCF feed system have established the following:

1. The flow of liquid from the WCF feed tank can be regulated at flows from 10-110 gph without process stream dilution using a single vortex restrictor operating in the non-vented mode.
2. Operation for extended periods is possible without plugging or flow rate upset, even with open-loop control.
3. Neither drying nor solids deposition were found to be a problem.
4. The less expensive and simpler device performed at least as well as a mechanical control valve and was not plugged by solids.

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