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A RECIPROCATING PUMP CHECK VALVE DESIGNED FOR SUPERCRITICAL WATER OXIDATION OF SLUDGES

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Summary

This paper describes the design and test of a reciprocating pump check valve suitable for supercritical water oxidation of sludges. Various designs of pump check valves exist, but few of them meet the requirement for regulating fluids containing particulates (slurries) at high pressures. Check valve leakage is a major problem in pumping particulate fluids. It is desirable to modify existing pump systems for a number of applications. Such was the case for pumping sludges in a novel bench-scale wastewater treatment process operated above the critical pressure of water (221.2 bar or 3207.4 psia).

Design and test of the sludge check valve were performed with an American Lewa diaphragm pump (Model HLM-1) which had a capacity of 1.5 g/s (0.2 lb/min) at its maximum working pressure of 600 bar (8700 psig). The tests were performed with sludge solutions containing up to 5.7 wt.% total solids and particle sizes up to about 100 μm (150 mesh). About one-third of the total solids consisted of fibrous materials as long as one tenth of an inch, which were not accounted in particle size measurement. The modified check valve has been successfully tested for more than 50 hours at a pressure level of 207-276 bar (3000 to 4000 psig) and flow rates ranging from 45 to 135 g/min (0.1 to 0.3 lb/min).

INTRODUCTION

Pumps are the heart of any continuous, high pressure process where a liquid feed is required. The mechanical capability of a pump is determined by three factors: discharge pressure, flow rate, and particle tolerance. Medium high pressure pumps (pressure range about 3000 to 10 000 psig) are available typically for "clean" liquids containing particulates less than 2500 mesh in size. At these pressures, most pumps have virtually zero particle tolerance. On the

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other hand, commercial slurry pumps can handle larger particulates (up to 10 mesh) with higher concentrations up to about 60 wt.% solid, but the discharge pressure reported in the literature is about 2400 psig [1,2].

Recent studies have shown that supercritical water provides an effective oxidation environment for detoxification of organic wastewaters and sludges in a totally enclosed treatment facility [3–7]. Supercritical water oxidation of sludges in a continuous-flow system requires special pumps which are capable of not only creating high pressures (3500 psig or higher) but also tolerating large solid particles (larger than 100 mesh). Current literature [1,8–10] and pump manufacturers' catalogs indicate that such pumps with a bench-scale capacity simply do not exist.

Based on their principle of operation, pumps are classified into two types: dynamic and positive displacement [11–13]. A typical example in the first category is the centrifugal pump in which pressure head is converted from kinetic energy. The second category includes the reciprocating (such as plunger, diaphragm) and rotating (such as gear, progressive-cavity) pumps. Most pumps that handle sludge and slurry at high pressures are of the positive displacement type, among which plunger and diaphragm pumps are most popular.

Both plunger and diaphragm pumps basically utilize the same principle of operation. The fluid is pumped through as a result of suction and discharge actions. Fluid movement is achieved by mechanically moving the plunger or diaphragm back and forth, and by regulating flow direction through a set of suction and discharge check valves. Most reciprocating pumps can generate 5000 to 10 000 psig pressures, but they are typically suitable for clean fluids which contain particulates than 6 μm (2500 mesh) in size. In some cases, up to 150 mesh size particles in the feed solution can be tolerated when special materials are used for plunger seals and check valves. Gear pumps allow little tolerance in the particle size because of restricted clearance between gears, and offer limited working pressure depending on the fluid viscosity. Both centrifugal and progressive-cavity pumps can tolerate solid particles (in order of 10 mesh or larger), but discharge pressure is inherently limited to less than 1000 psig. Higher operating pressures may be achieved with special designs as in the case of a multiple stage centrifugal pump which is capable of pumping 200 mesh coal slurry (up to 50 wt.% solid) at a flow of 567.8 m^3/h (2500 gal/min) as high as 3000 psig [14]. However, erosive corrosion in centrifugal pumps has always been a problem due to the high fluid velocity.

As one would expect, the check valve is as important to a reciprocating pump as the cuspid valve to a heart. A check valve allows the process fluid to flow in only one direction to build up process pressure. All check valves are constructed with either metal-to-metal or metal-to-nonmetal contact. The former type may be referred to as a ball check valve, as it consists of a metal ball and seat. The later usually consists of a metal ball and an elastomer O-ring attach-

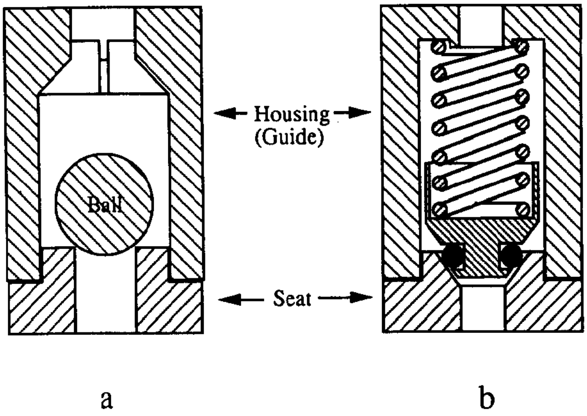


Fig. 1. Typical check valve designs: (a) hard-seated, and (b) soft-seated.

ment supported by a spring. Figure 1 illustrates typical designs for (a) hard-seated and (b) soft-seated check valves.

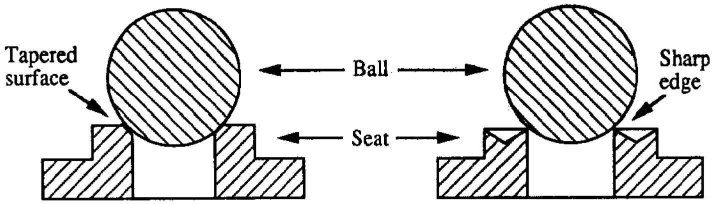
The essential requirement for a sludge check valve is its sealing ability in contact with solid particles. When pumping sludge or slurry, existing hard-seated (metal-to-metal) check valves generally fail to stop back-flow as a result of the "bridging" effect. The use of soft-seated (slush-type) check valves in slurry pumps have been successful in some commercial-scale operations [2], where an elastomeric O-ring is used to cover particles entrapped on the sealing face.

In this study, the design modification was based on a hard-seated check valve because it involved a lesser number of components, more modification options, and longer operational life as compared to a soft-seated valve. A diaphragm pump (American Lewa Model HLM-1) rated at 0.2 lb/min at its maximum working pressure of 8700 psig was used to test the modified check valve using both industrial and municipal sludges. This diaphragm pump was a better choice for sludges because it had no seal wearing problem as compared to a plunger pump.

Modified check valve design

Figure 2(a) depicts a typical hard-seated check valve enlarged at its seal section [15]. Note that the ball seat is a tapered surface which has been carefully lapped to fit the ball with great precision. It is this contact surface that makes this valve inefficient, if not impossible, when particulates are present. Therefore, this type of ball check design is the least desirable sealing arrangement for high pressure application.

For sealing at high pressures, the configuration and size of the contact sur-



a b

Fig. 2. Enlarged ball check sealing designs: (a) conventional (tapered seat), and (b) modified (sharp-edged seat).

face between any two components are crucial. In principle, sealing at a point is the best, sealing on a line is second choice, and sealing on a surface is undesirable. However, the point-contact sealing is not practical for sludge service. The only option left for improvement of the conventional check valve is to provide a line-contact sealing as shown in Figure 2(b). In this case the modified check valve seat has a 60° ridge with a tolerance of about 0.001 inch radius. The outside diameter and height of the American Lewa check valve are about 0.591 inch, respectively, and the diameter of the ball is 0.276 inch. It is expected that the ridge acts as a "knife", assuming the construction material is much harder than the particulates in the pumping fluid. This sharp edge separates particulates to either side of its surface as the ball moves downwards and finally seals on the contact line. At the same time, the clearance of the valve guide (housing) and configuration of the valve stop are also key factors for a functional sludge check valve. Modifications in these two aspects have also been researched, but are not covered in this paper.

Modified check valve performance

The American Lewa's pump head design provided accommodation of four check valves (two in the suction end and two in the discharge end) installed in series. The modified check valve housing, made of Stainless Steel 316, had the same overall dimension as that of the American Lewa's. the check ball in the original American Lewa check valve was used without change.

Both industrial (activated) and municipal (digested) sludges were used to test the modified check valve. Table 1 provides some characterizations of the industrial sludge used for the test.

In the performance test, mass flow rates of water and sludges with four different total solids (TS) contents were measured at 3500 psig pressure. The temperature at the pump head was about 75°F (24°C). Table 2 summarizes the test results.

TABLE 1

Properties of the industrial sludge used for check valve testing

Composition	About 70 wt.% total solids are volatile solids, and a large portion of the remaining 30 wt.% total solids is paper fibers.
Particle size distribution (fibers were not included)	80% particles by volume are between 170 and 1250 mesh, 80% particles by number are between 625 and 2500 mesh.
Density	920 kg/m^3 (57.4 lb/ft^3) at 5.7 wt.% total solids

TABLE 2

Flow rates at the maximum pump capacity setting and various sludge solid concentrations

	Solid concentration (%)				
	0 (water)	1.2	2.1	3.9	5.7
Flow rate (lb/min)[a]	0.275	0.302	0.302	0.302	0.302

[a]1 lb/min=7.57 g/s.

The increase in flow rate when pumping sludges suggested that particulates in sludge may have actually helped to decrease valve slippage. The total solid concentration, as well as type of sludges, had little effect on the mass flow rate. After about 50 hours of testing, the check valves were disassembled and examined. Some wearing at the contact rim was observed, which has been a common problem for all slurry check valves [16]. The width of the flattened rim was about 0.004 inch, compared to the initial machining tolorance of 0.001 inch. However, the wearing of the sealing line did not significantly affect the check valve performance. If needed, the modified check valves can be made of materials (with or without heat treatment) harder than Stainless Steel 316.

Conclusions

This experimental investigation demonstrated that the modified check valve was capable of pumping sludge up to about 6 wt.% total solids in a pressure range form 3000 psig to 4000 psig. The check valve may well be functional at higher sludge concentrations and higher discharge pressures. It was expected that further testing of this design concept would be necessary and useful in order to develop simple, yet effective, check valves and to increase valve selection gamut for laboratory-scale as well as large-scale sludge pumps.

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