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Design and Test of a Diaphragm Pump
for Liquid Metals

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Design and Test of a Diaphragm Pump

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ABSTRACT

Details are provided on the construction and operation of a two-stage diaphragm pump successfully used for the first time in liquid metal service. From the results of a 5,376 hr. test of the pump it was concluded that it is well suited to the pumping of liquid metals at low flow rates where pulsating flow can be tolerated and also where remote operation is required. Operating temperatures and pressures are limited only by the availability of suitable materials of construction.

Design and Test of a Diaphragm Pump for Liquid Metals^{*}

The use of liquid metals in liquid metal fueled reactors has created the need for suitable pumps not only for the reactor itself, but also for the laboratory scale forced convection loops needed for design and development purposes. Although these small scale loops are usually used to determine corrosion, heat transfer, and fluid flow characteristics, they have also been useful in evaluating process equipment such as distillation units for the separation of liquid metals.

Three types of pumps which are suitable for liquid metal work are centrifugal, electromagnetic, and diaphragm. Although several good reviews of centrifugal and electromagnetic pumps are available (1-4, 7-9, 11-14), to the authors' knowledge no prior data on diaphragm pumps for high-temperature liquid metal service have been published.

GENERAL DESCRIPTION OF PUMP SYSTEM AND TEST LOOP

The test system consisted of a high temperature loop in which lead-bismuth eutectic was circulated by means of a 2-stage modified diaphragm-type proportioning pump similar to the type commonly used in the chemical industries. Figures 1 and 2 are schematic drawings of the test system.

The pump was manufactured by the Lapp Insulator Company, LeRoy, New York, to meet specifications established by the authors. It consists of a standard model CPS-2 Pulsafeeder, a remote diaphragm

^{*}Contribution No. 1159. Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.

Fig. 1. Schematic assembly drawing of pump, remote diaphragm assembly and loop.

Fig. 2. Two stage diaphragm pump system.

head, and a check valve assembly, the latter two being capable of high temperature operation. The CPS-2 acts as a pulse generator and operates near room temperature. It makes use of a normal hydraulic fluid (oil) to transmit the pulse. The oil fills the gear box, cylinder and that portion of the system up to the first diaphragm. The space on the other side of this diaphragm, as well as that in the lower half of the remote high-temperature diaphragm and in the tube connecting the two, is filled with the eutectic composition of sodium-potassium (NaK) alloy which contains 78% potassium by weight. The upper half of the remote, high-temperature head is filled with the process fluid; in this case lead-bismuth eutectic alloy. The outlet from this half of the head is connected to the ball check valve assembly in the loop.

Pulses produced by the CPS-2 pump are transmitted by the NaK to the high temperature diaphragm which in turn transmits the pulses to the process fluid. The process fluid pulsations are then converted to net flow by the check valve assembly.

The remote head is immersed in a heated liquid metal bath for purposes of temperature control and positioned horizontally to facilitate piping. Figure 3 shows the remote head in the steel bath container, which was totally enclosed in firebrick. The ball check valve assembly and the CPS-2 pump head are connected to the remote head by flanges of a special raised face design developed by Clifford and Burnet (5).

The remote high-temperature head and check valve assembly is especially designed to reduce the number of joints and avoid welding

Fig. 3. Remote diaphragm assembly in liquid metal bath container and insulating brickwork.

Fig. 4. Ball support and ball after 5,376 hr. of operation.

wherever possible as the material used for construction was somewhat difficult to weld, requiring a special technique.

The test loop consists of a charge tank, an expansion tank, a cold trap, a heat exchanger which is used to meter flow and three electrical resistance furnaces used to maintain the desired loop temperature.

PULSE GENERATOR

The standard model CPS-2 Pulsafeeder pump used to generate the pulse in this system is of the reciprocating oil-pulse type. This pump consists of a piston 1.5 in. in diameter in a cylinder which operates submerged in oil. The piston has a constant stroking speed of 58 strokes per min. and the pumping rate is established by the length of piston stroke. The piston stroke length is continuously variable while the pump is either idle or operating from 0 to 100% capacity.

Since the piston handles only oil, no stuffing box is required and only cup seals are incorporated. Any leakage past the cylinder is replaced on every suction stroke through a vacuum compensator valve which draws in replacement oil from the oil reservoir. If any excess pressure is built up in the system, it is relieved automatically by a pressure relief valve which blows off oil under excess pressure ahead of the piston back into the oil reservoir. The pressure relief valve is designed to open approximately 15% above design pressure.

The capacity of the CPS-2 Pulsafeeder pump used is 42.4 gal. per hr. at 0 psig and a stroke length of 1.6 in. Increasing the discharge pressure decreases capacity approximately 1% per 100 psig

increase. The pump is described (10) as having a maximum continuous pressure rating of 150 psig and, since it is a single acting piston positive displacement unit, suction pressures do not affect the discharge pressure rating.

Because of the reciprocating drive, the pressure-time curve is sinusoidal. The sinusoidal nature of this curve reduces accelerations of the fluid at the beginning and end of each stroke to a minimum and thus the operation of the system is both smooth and quiet.

HIGH-TEMPERATURE REMOTE HEAD

The remote head is designed to meet four major requirements.

These are:

1. High-temperature (300-800°C) operation
2. No external or internal leakage of the process fluid (Pb-Bi eutectic) as well as the NaK intermediate system
3. Ease of disassembly for inspection and maintenance
4. A maximum period of continuous operation.

The remote head is of a bolted design and is constructed entirely of type 446 stainless steel (SS). This type of steel was selected on the basis of corrosion data since published by Clifford and Burnet (6).

The bolted design offers one big advantage over the welded type head in that it is easier to replace the diaphragm in case of failure. To service a remote head of welded design it would be necessary to cut open the welds and then again reweld before returning it to operation. This is particularly objectionable with type 446 SS as the techniques of welding are quite critical. Also in a welded design it is

necessary to be careful in heating as uneven heating will cause uneven expansion which can lead to cracked welds. Due to the fact that the tensile strength of type 446 SS drops from a value of approximately 93,400 psi at 316°C to only 4,590 psi at 870°C and an extended period of continuous operation was desired, the remote head was designed with heavy bolts, thick flanges and a larger and thicker diaphragm than otherwise might have been used. Thus it is considerably larger than the low temperature head as can readily be seen in Figs. 1, 2 and 3. Specifications for the remote head were 50 psig discharge pressure at 816°C.

The metal-diaphragm is the most important part of the remote head and as such, received primary consideration. The dish contour is of the two radii contoured design which does a better job of supporting the diaphragm within its stress limits than the so-called free deflection contour. The 0.030 in. thick diaphragm is 12 in. in diameter and has a calculated stress of 16,500 psi for full deflection. However, due to the fact that the volumetric displacement of the remote head is approximately 6 cu. in. while the displacement of the pulse generator piston is 2.8 cu. in. per stroke, there is considerable overage in the remote head. Thus, the diaphragm never has full deflection and operates with an estimated actual stress of approximately 10,000 psi.

A leak-tight seal is maintained between the two halves of the remote head by means of polished, raised bearing surfaces on the face of each half so that the assembly is similar to a pair of raised-face flanges with the diaphragm acting as a gasket. The remote head is immersed in a heated liquid metal bath for purposes of temperature control (Fig. 3).

LOW-TEMPERATURE HEAD

The low temperature head is an integral part of the CPS-2 Pulsafeeder and is of welded design. The heads, as well as the 0.021-in. thick diaphragm which is approximately 10 in. in diameter, were manufactured from type 316 SS. The dish contour is of the two radii contoured design.

CHECK VALVES

The entire check valve assembly with the exception of the balls and tie bars was manufactured of type 446 SS. The balls were of type 440 SS and the tie bars of 316 SS.

Due to the fact that the type 440 SS balls are lighter than the Pb-Bi eutectic process fluid, these balls would float above the valve seats if the assembly were operated in the normal manner, i.e. flow from bottom to top instead of from top to bottom as shown in Fig. 2. The density of the Pb-Bi eutectic at 375°C is 10.2 g/cm^3 and that of type 440 SS approximately 7.7 g/cm^3 . Therefore, the assembly was inverted; the direction of flow being from top to bottom. Figure 4 is a photograph showing the condition of a ball support and a ball after 5,376 hr. of continuous operation.

The diameter of the ball is 0.75 ± 0.00005 in. and the diameter of the seat 0.562 in. The ball to seat ratio is then 4:3. The ball cage is 1 in. in diameter and with the 0.75-in. ball working in it has a clearance on each side of the ball of approximately 0.125 in. This is larger than normally used on a liquid pump. However, due to the nature of the process fluid the extra clearance was designed to make sure that any

impurities or scale would not restrict the ball movement. The lift of the ball is approximately 0.125 in. The balls are hardened and in the range of C-60 to C-65 hardness. The seats are of type 446 SS and approximately of 200 Brinell hardness.

OPERATION OF TEST SYSTEM

The first step in putting the system into operation after assembly was to fill the NaK intermediate section. This was accomplished by evacuating the section to less than 0.01 micron and then allowing the NaK under 5 psig nitrogen pressure to flow into the section. Any entrapped gas was allowed to accumulate in the vertical standpipe located on top of the low-temperature head. Figure 2 shows the vacuum arrangement and standpipe. The remote head and test loop were next brought up to operating temperature and the Pb-Bi eutectic charged to the loop using the same technique as was employed in filling the NaK section.

The pump was then started and the system operated continuously for 5,376 hr. without serious difficulty.

It was necessary to install cooling coils on the face of the low-temperature pump head to absorb the heat conducted from the high-temperature remote head. The low-temperature head was maintained near room temperature by circulating cooling water through the coils.

On two occasions during operation the cooling water supply was interrupted for several hours which left the low-temperature head without sufficient cooling. This situation was corrected by temporarily reducing the temperature of the loop from 575 to 350°C and reducing the remote head constant temperature bath from 350 to 190°C. This minimized the heat flow due to conduction from the remote head to the pump

head. Further cooling of the pump head by forced air convection was achieved by directing two electric floor fans on the head. In both instances the pump continued to operate properly, and was easily brought back to normal operating conditions when the water supply was restored.

Except for the above cases the operating conditions were not changed during the run. The expansion tank temperature was held at 575°C, the cold trap at a temperature of 370°C, and the remote head at 350°C.

Flowrate was determined by calibrating the remote head with water prior to start-up. The flowrates thus determined were checked, once the loop was in operation, by carefully measuring, in a small heat exchange section of the loop, the heat removed from the eutectic and its temperature drop.

Based on the pump calibration, the flowrate was held at 0.6 gal. per min. throughout the test. The thermal head developed in the loop was negligible and did not contribute significantly to the pumping action. It was impossible to maintain an accurate check on the flowrate figure due to a failure of thermocouples in the heat exchange section used to meter flow. However, as far as could be determined by the constancy of the temperature profiles of the loop, and condition of the ball check valves after disassembly of the loop, there was no loss in pump capacity during operation.

RESULTS

The pump system operated continuously and without failure for over seven months (5,376 hr.). During the entire test no irregularity in the operation of the diaphragm was evident. At no time were standing

waves or hammer encountered. Both diaphragms operated quietly and smoothly without any trace of flutter or non-uniform progress of the diaphragm.

The ball check valves operated satisfactorily and quietly except for an occasional rattling of the balls. The balls were not seriously scored and their sphericity checked to be $0.75 + 0.0001$ in. The valve seats showed slight wear but remained perfectly circular thereby maintaining a tight seal.

CONCLUSIONS

Experience to date indicates that this type of pump is ideally suited to the pumping of lead-bismuth eutectic and probably other liquid metals at low flowrates where pulsating flow can be tolerated. Because it is a positive displacement pump, it is also an accurate metering device.

Once the pump is put into operation it needs only routine maintenance provided the proper materials of construction have been selected. This, plus ease of control, makes remote operation both feasible and simple.

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FIGURE CAPTIONS

- Fig. 1. Schematic assembly drawing of pump, remote diaphragm assembly and loop.
- Fig. 2. Two stage diaphragm pump system.
- Fig. 3. Remote diaphragm assembly in liquid metal bath container and insulating brickwork.
- Fig. 4. Ball support and ball after 5,376 hr. of operation.

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