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Manuscript received August 2, 1966; revision received September 23, 1966; paper accepted September 23, 1966. Paper presented at A.I.Ch.E. Detroit meeting.

Flow Work Exchanger

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In a high-pressure process, feed streams are continually pressurized and product streams are continually depressurized. A flow work exchanger offers an efficient and economical scheme for simultaneously pressurizing a fluid stream and depressurizing a substantially equivalent volume of another fluid stream. Its applicability is however limited to fluids under condensed state. A flow work exchanger uses a displacement vessel to form a closed loop with a processing system. The displacement vessel is alternately filled by a low-pressure feed and a high-pressure product, both pressurized and depressurized, respectively, by substantially nonflow processes. The pressurized feed is pushed into the processing system by the high-pressure product stream and the depressurized product stream is pushed out of the displacement vessel by the low-pressure feed stream. The application of a flow work exchanger is illustrated by means of several high-pressure processes and the direct and indirect advantages obtainable are described.

Many physical and chemical processes are carried out under high pressure. A reverse osmosis process (*1* to *5*), a freezing process based on high-pressure inversion of the order of melting points (*6*), manufacture of phenol by the hydrolysis of chlorobenzene (*7*), and hydrogenation of oil and coal (*8*) are some of the typical high-pressure processes in which at least part of the reactants and at least part of the products form condensed fluid streams. In the following discussions a condensed fluid will be used to mean any substance under condensed state that has sufficient fluidity to be handled by a pump; it may be a liquid, a slurry, or a paste.

The disadvantages of the conventional schemes of flow pressurization can be attributed to the following reasons:

1. The magnitude of the shaft work involved in a high-pressure pump or a turbine is high. The energy loss in a pumping operation increases with the magnitude of the shaft work. Therefore, both the reduction of the magnitude of shaft work and the improvement of pumping efficiency are important to the reduction of energy loss in a pumping operation. Similar arguments also apply to a depressurization operation.

2. *Pumping efficiency is low.* The efficiency of a centrifugal pump is usually less than 80% and the efficiency of a positive displacement pump is usually less than 90%.

3. Due to the large amount of shaft work involved, large machine members and large driving mechanisms are required. Due to the large pressure differential involved, elaborate finishing and packing are required in manufacture, which leads to high equipment costs.

A *flow work exchanger* herein described applies to a simultaneous pressurization of a condensed fluid *A* and depressurization of a condensed fluid *B*. The *A* and *B* fluids are pressurized and depressurized, respectively, by substantially nonflow processes. The movements of the fluids are conducted against small pressure differentials and thus $\Delta(PV)$ values for the movements of fluids are small and the shaft work is greatly reduced. This scheme of flow work exchange was first introduced by Cheng and Cheng in connection with their "freezing process which is based on the high-pressure inversion in the order of melting points" (*6*).

A flow work exchanger can exchange flow work between substantially equivalent volumes of two condensed fluids. Thus, high-pressure processes are classified into two types. Type A: A process in which the sum of the volumes of the high-pressure products in the condensed state is less than the sum of the volumes of the low-pressure feeds in the condensed state. Type B: A process in which the sum of the volumes of the high-pressure products in the condensed state is greater than the sum of the volumes of the low-pressure feeds in the condensed state.

The excess volumes will be referred to as the excess volume of feed and excess volume of product, respectively. The excess volume of feed and the excess volume of product have to be pressurized and depressurized, respectively, conventionally.

The optimal operating condition of a high-pressure process is greatly influenced by the efficiencies of the pressurization and depressurization operations. In addition to the immediate cost reduction obtainable by the adoption of flow work exchangers in a process where the operating condition is substantially left unaltered, cost reduction can also be realized by operating the process under the new optimal operating condition. This further cost reduction may be very significant in many cases.

FLOW WORK EXCHANGER

Figure 1 illustrates a high-pressure processing system into which a feed is introduced by a pump J_1 and from which a product is discharged by a turbine J_2. The pump operates between pressures $(P_L)_1$ and $(P_H)_1$; the turbine operates between $(P_H)_2$ and $(P_L)_2$. Quantitative discussions will refer to a high-pressure process operated at 1,500 lb./sq.in. gauge.

When a condensed fluid is pressurized without phase change to a high pressure, the reversible shaft work received by the fluid in a flow process $-w_f = \int Vdp$ is on the order of 200 times the corresponding value for a nonflow process $-w_{nf} = -\int pdV$. This is due to the noncompressibility of a condensed fluid; a liquid shrinks by about 1% upon the application of 100 atm. pressure. Similar statements can be made for the depressurization operation.

The reversible shaft work for the pump and turbine, shown in Figure 1, can be represented by

$$(-w_1)_f = \int_{(P_L)_1}^{(P_H)_1} Vdp = (P_H)_1 \cdot (V_H)_1 - (P_L)_1(V_L)_1 - \int_{(P_L)_1}^{(P_H)_1} P \cdot dV \quad (1)$$

$$(+w_2)_f = \int_{(P_L)_2}^{(P_H)_2} Vdp = (P_H)_2 \cdot (V_H)_2 - (P_L)_2 \cdot (V_L)_2 - \int_{(P_L)_2}^{(P_H)_2} P \cdot dV \quad (2)$$

Each equation shows that the shaft work for a flow process is the sum of the shaft work for a corresponding nonflow process and the difference in the flow work terms under the high and the low pressure $\Delta(PV)$. They also show that the large values of the shaft work for the reversible pressurization and the depressurization should be attributed to the large values of the differences in flow work terms $\Delta(PV)$'s.

A flow pressurization may be considered as a superposition, a nonflow pressurization, and a movement of fluid. The $|\Delta(PV)|$ term is large, because the movement of fluid takes place across a large pressure differential between $(P_L)_1$ and $(P_H)_1$. Similarly, for flow depressurization the $|\Delta(PV)|$ term is large because of the movement across a large pressure differential between $(P_L)_2$ and $(P_H)_2$.

For flow pressurizing a condensed fluid and flow depressurizing another fluid simultaneously, as shown in Figure 1, it is possible to arrange the flow system so that movements of fluids take place across small pressure differentials; that is, between $(P_H)_1$ and $(P_H)_2$ and between $(P_L)_1$ and $(P_L)_2$. Then the $|\Delta(PV)|$ terms become very small, and the shaft work becomes small. The shaft work can approach the values of the corresponding nonflow processes.

The simultaneous flow pressurization and flow depressurization operation then involves the following steps: (1) low-pressure and small-pressure differential $(P_L)_1 - (P_L)_2$ displacement operation; (2) substantially nonflow pressurization of the feed; (3) high pressure and small pressure differential $(P_H)_2 - (P_H)_1$ displacement operation; (4) substantially nonflow depressurization of the product.

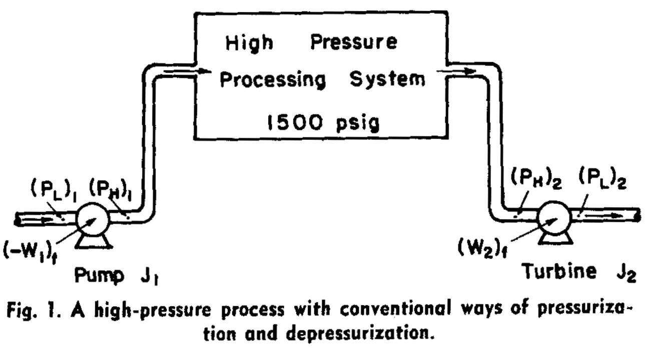

Fig. 1. A high-pressure process with conventional ways of pressurization and depressurization.

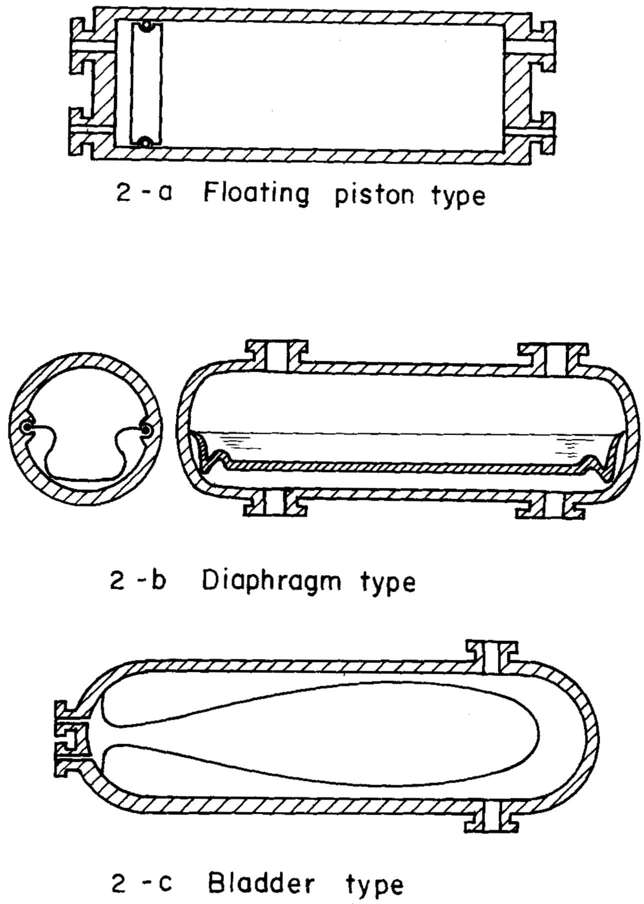

Fig. 2. Construction of a displacement vessel.

In the following discussions the first and third steps will be referred to as the low-pressure displacement operation and the high-pressure displacement operation, respectively. The entire operation will be called the flow work exchange operation. A fluid to be pressurized in a process may exchange flow work with another fluid to be depressurized in the same process or in other processes. The equipment will be called the flow work exchanger.

A displacement vessel equipped with a floating solid partition (or separator) is the heart of a flow work exchanger. This separator or partitioner may be a piston, a diaphragm, or a bladder. In the piston type of displacement vessel (Figure 2*a*), the piston is similar to that in a hydraulic cylinder. However, the floating separator in the displacement vessel has no piston rod and is used to separate two fluids at nearly equal pressures. Since the movable piston is not used to pressurize the fluid and the problem of fluid leakage is minor, the floating piston can be simply constructed, with no elaborate finishing being required. As shown in Figure 2*b*, a diaphragm may be installed to separate the operating fluids. The displacement vessel would operate like a diaphragm type of gas meter. Alternately, in the bladder type, a bag may be placed in the displacement vessel (Figure 2*c*). Further possibilities are the use of an immiscible fluid to separate the operating fluids or with no separator used if vessels with a large length to diameter ratio are used.

The displacement vessel is alternately filled by a low-pressure feed and a high-pressure product, and the con-

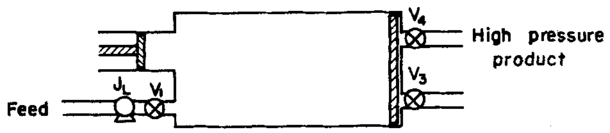

Fig. 3—a

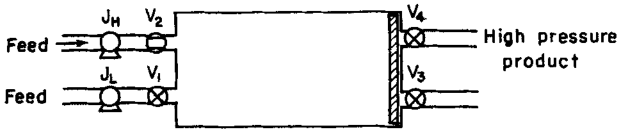

Fig. 3—b

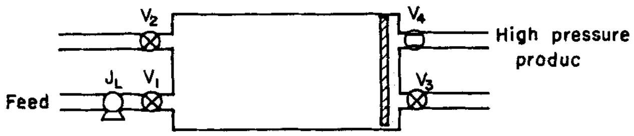

Fig. 3—c

Fig. 3. Nonflow pressurization of fluid in a displacement vessel.

tents are pressurized and depressurized, respectively, by substantially nonflow processes. A nonflow pressurization can be attained in one of the following ways.

1. As regards Figure 3*a*, a displacement vessel is equipped with a small pocket with a piston. When the displacement vessel and the pocket are filled with the low-pressure feed by pump J_L, valve V_1 is closed and the piston is advanced within the pocket to pressurize the contents.

2. As regards Figure 3*b*, when the displacement vessel is filled with low-pressure feed by pump J_L, valve V_1 is closed and an additional amount of feed is pumped in through a high-pressure pump J_H to compensate for the volume shrinkage of the fluid due to the pressurization.

3. As regards Figure 3*c*, when the displacement vessel is filled with the low-pressure feed, valve V_1 is closed and some high-pressure product is admitted into the vessel through V_4 to pressurize the contents. Valves V_2 and V_3 are in the closed position during this operation.

ILLUSTRATION OF A FLOW WORK EXCHANGER

Figure 4 illustrates a flow work exchanger in connection with a high-pressure process, which belongs to type A. As has been mentioned, the excess volume of feed in a type A process has to be pressurized in a conventional way.

A flow work exchanger consists of one or more displacement vessels (two as shown in Figure 4), check valves (V_1, V_2, V_3, and V_4), control valves (V_5, V_6, V_7, and V_8), a low-pressure low head pump (J_1), and a high-pressure low head pump (J_2). The pump J_2 is used to recover the pressure drop of fluid during its passage through the processing system and maintains $(P_H)_2$ higher than $(P_H)_1$ by an amount sufficient to carry out a high-pressure displacement operation to be described. Alternately, the pump J_2 may be installed at the inlet side of the high-pressure system such as location Y in Figure 4. The pump J_1 is used to maintain $(P_L)_1$ somewhat higher than $(P_L)_2$ to carry out a low-pressure displacement operation to be described. The high-pressure pump (J_3) is used to pressurize the excess part of the feed. The feed end and product end of a displacement vessel will be called *a* end and *b* end, respectively.

Each displacement vessel is operated cyclically in the following steps.

Step 1: Substantially nonflow depressurization. The displacement vessel O_1 is filled with the high-pressure product. By closing the valve V_5 and opening the valve V_6, the content in the displacement vessel is depressurized and some product fluid in the amount corresponding to the volume expansion due to the depressurization flows out of the vessel through valve V_6. This operation takes a very short time. The check valves V_1 and V_2 are in the closed position during this operation.

Step 2: Low-pressure displacement operation. When the pressure in the vessel drops below $(P_L)_1$, the check valve V_2 opens and the low-pressure feed flows in through V_2 and the depressurized product flows out of the vessel through the valve V_6. The solid partitioner M_1 moves from the *a* end to the *b* end. The valves V_1 and V_5 are kept closed. At the end of this operation the vessel is filled with low-pressure feed.

Step 3: Substantially nonflow pressurization. The displacement vessel O_2 is now filled with the low-pressure feed. One of the nonflow pressurization schemes described in the previous section may be used to pressurize the content; however, scheme 3 is used here. With the valve V_8 closed and the valve V_7 open, some high-pressure product flows into the vessel to pressurize the content. This operation takes a very short time, because only a small amount of fluid sufficient to compensate for the volume shrinkage has to be introduced. During this operation the check valves V_3 and V_4 are in the closed position.

Step 4: High-pressure displacement operation. When the pressure in the vessel exceeds $(P_H)_1$, the valve V_3 opens and the high-pressure product flows continually into the vessel through V_3 and the pressurized feed fluid is displaced into the high-pressure processing system. The solid partitioner M_2 moves from the *b* end to the *a* end. At the end of this operation the vessel is filled with high-pressure product. Then, it returns to step 1 and starts over again.

The displacement operations, steps 2 and 4, occupy most of the time in an operating cycle and each nonflow process, step 1 or step 3, takes rather short periods of time. Thus when two displacement vessels are operated with proper timing, fluid flow through the processing system will be continuous except for the short periods during step 1 and step 3 and the time taken in operating the valves. These disturbances may be lessened by accommodating a small accumulator in the system.

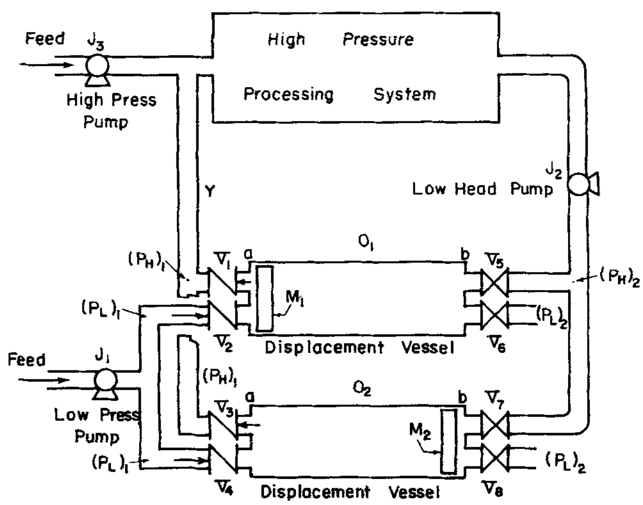

Fig. 4. A high-pressure processing system incorporating flow work exchangers.

It may be noted that a three-way valve may be used to replace a pair of two-way valves, either V_5 and V_6 or V_7 and V_8. Furthermore a four-way valve may be used to replace the four valves, V_5 through V_8.

Flow work exchangers may also be used in connection with a type B process. In this case, the excess volume of condensed product has to be depressurized in a conventional way.

EFFICIENCY OF A FLOW WORK EXCHANGER

The operation of a flow work exchanger described in the last section can be illustrated by an idealized indicator diagram shown in Figure 5 and the lost work involved in each step can be estimated from the figure.

Referring to the figure, AB represents the volume of the displacement vessel V_D, AX represents the volume of the feed V_F in the vessel, and BX represents the volume of the product V_P in the vessel. Therefore

$$V_F + V_P = V_D \quad \text{and} \quad AX + BX = AB$$

The operational steps illustrated in the last section can be represented on the indicator diagram as follows.

1. Substantially nonflow depressurization. This operation is represented by 7-8 in Figure 5. Point 7 represents the situation where the displacement vessel is filled with product fluid at pressure $(P_H)_2$. When the valve V_6 is open, the content is depressurized and its volume expands from 7 to 8, and its pressure drops to $(P_L)_2$. A volume of product fluid in the amount of 9-8 flows out of the vessel.

2. Low-pressure displacement operation. This operation is represented by $3 \rightarrow 4$ and $9 \rightarrow 10$ in Figure 5. They show that feed fluid enters the vessel at $(P_L)_1$ and product fluid leaves the vessel at $(P_L)_2$.

3. Substantially nonflow pressurization. This operation is represented by $4 \rightarrow 1$ and $10 \rightarrow 6 \rightarrow 6'$. It shows that the high-pressure product is introduced into the vessel in the amount represented by 6-6′ to compress the feed in the vessel to $(P_H)_1$.

4. High-pressure displacement operation. This operation is represented by $1 \rightarrow 2$ and $6' \rightarrow 7$ in Figure 5. They show that the product fluid enters the vessel at $(P_H)_2$ and the feed leaves the vessel and is moved into the processing system at $(P_H)_1$.

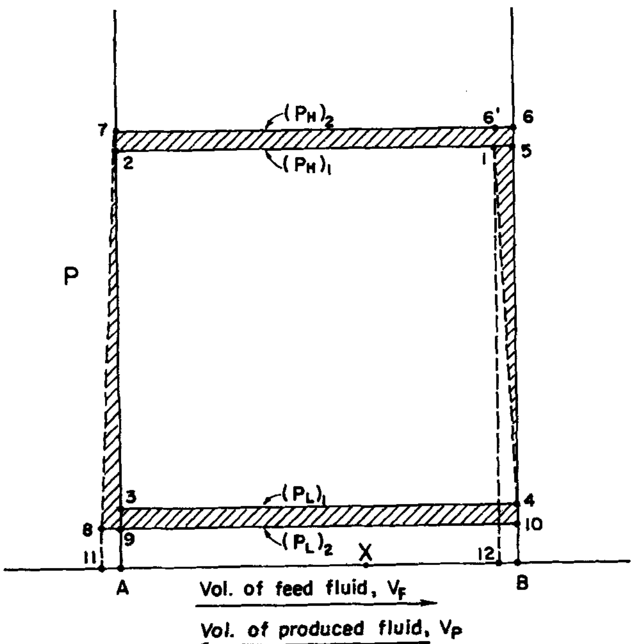

Fig. 5. Schematic indicator diagram of a flow work exchanger.

The lost work involved in the steps is represented by the shaded areas. Area 7-8-9 is the work of expansion in step 1; it is so small that it may well be unrecovered to simplify the operation. Area 4-5-6-6′-1 is the irreversibility involved in step 3; and areas 3-9-10-4 and 7-2-1-6′ represent the lost work involved in the displacement operation, that is, step 2 and step 4.

The net work required in simultaneously pressurizing one fluid from $(P_L)_1$ to $(P_H)_1$ and depressurizing another fluid from $(P_H)_2$ to $(P_L)_2$ is zero in a reversible case. In an actual operation the net work to be supplied is equal to the sum of the lost work. The net work to be supplied in operating a flow work exchanger thus is equal to the sum of lost work shown by the shaded areas in Figure 5, lost work due to leakage of fluid due to volume inefficiencies of valves, and that due to the inefficiencies of the pumps J_1 and J_2.

For a flow work exchange between an equal volume of a low-pressure (1 atm.) feed and a high-pressure (100 atm.) product, the net work to be supplied is in the order of 5 to 10% of the value of the reversible shaft work in the pressurization.

The inefficiency of a flow work exchanger will be defined as the ratio of the net work to the reversible shaft work in the pressurization. The quoted inefficiency value is estimated from reasonable performances of the component parts of a flow work exchanger as follows:

1. Referring to Figure 5

$$(P_H)_2 - (P_H)_1 = 5 \sim 10 \text{ lb./sq.in.}$$
$$(P_L)_1 - (P_L)_2 = 5 \sim 10 \text{ lb./sq.in.}$$

2. Volume shrinkage and volume expansion in the nonflow pressurization and depressurization operations = 1 ~ 1.5%.

3. Valve efficiencies = 98 ~ 99%. A high valve efficiency can be expected because of the less frequent operation as compared with a valve in a conventional pump.

4. Efficiencies of pumps J_1 and J_2 = 80%; efficiencies of motors = 90%.

When a conventional pump and a turbine are used in the pressurization and depressurization operation (Figure 1), the net work required can be calculated by the following equation:

$$-w_{\text{net}} = \frac{\int_{P_L}^{P_H} Vdp}{\eta_m \cdot \eta_p} - \eta_t \cdot \int_{P_L}^{P_H} Vdp = \left(\frac{1}{\eta_m \cdot \eta_p} - \eta_t \right) \int_{P_L}^{P_H} Vdp$$

where η_m, η_p, and η_t are motor, pump, and turbine efficiencies, respectively. Assuming $\eta_p = 80\%$, $\eta_t = 80\%$, and $\eta_m = 90\%$, the net work to be supplied is 60% of the reversible shaft work in the pressurization. Even assuming $\eta_p = 90\%$, $\eta_t = 90\%$, and $\eta_m = 90\%$, the net work to be supplied is 35% of the reversible shaft work in the pressurization. The inefficiencies of the operations are thus 60 and 35%, respectively. Therefore, it can be seen that a flow work exchanger is a very efficient scheme for simultaneous pressurization and depressurization of condensed fluids.

As is seen in Figure 5 flow work $(P_H)_2 V$ (that is, area A-B-6-7) is utilized to supply the work required in the nonflow pressurization of the feed $- \int pdV$ (that is, area 10-1-12-B) and the flow work of the feed $(P_H)_1 V$ (that is, area A-2-1-12). And the work recoverable in the nonflow depressurization of the product fluid (that is, area A-7-8-11) is not directly exchanged with the feed fluid. These are the reasons for calling this scheme a flow work exchanger.

EXAMPLES OF THE APPLICATION OF FLOW WORK EXCHANGE

Reverse Osmosis Desalination Process

In a reverse osmosis process (*1, 2*), seawater is pressurized and introduced into a reverse osmosis cell and the reject solution is depressurized. A system analysis of a single-stage operation has been worked out (*10*) and extended to a multistage operation (*11*). In the analysis the membrane permeability is assumed to be 0.86×10^{-4} cu.ft./(sq.ft.)(hr.)(lb./sq.in.) and linear cost relations are assumed. An optimization calculation has been applied to its operation and a quantitative discussion of the advantages of the adoption of a flow work exchanger has been made. The result of the study shows that the optimum operating condition is significantly shifted by the introduction of a flow work exchanger. When conventional ways of pressurization and depressurization are used, the optimum operating condition is: operating pressure = 1,260 lb./sq.in., concentration of reject brine = 5.5%, membrane area to feed ratio = 0.117 sq.ft./(lb.$_m$)(hr.), and water production cost = 40.2¢/1,000 gal. When a flow work exchanger of 10% inefficiency is used the optimum operating condition becomes: operating pressure = 1,200 lb./sq.in., concentration of the reject solution = 4.6%, membrane area to feed ratio = 0.065 sq.ft./(lb.$_m$)(hr.), and the water production cost = 30.4¢/1,000 gal. The calculated saving in the water production cost is 9.8¢/1,000 gal., of which a significant amount (1.7¢/1,000 gal.) is due to changing the operating condition to the new optimum operating condition.

A Freezing Process Based on the Inversion of Melting Points Due to Applied Pressure

This new freezing process developed for the desalination of seawater, brackish water, and other aqueous solutions utilizes a unique way of upgrading heat energy. Only condensed phases are involved in the process (*6*). This method of upgrading heat energy takes advantage of the abnormal melting point curve of water. Water melts at a lower temperature under a higher applied pressure (that is, $(dP/dT)_{\text{melting}} < 0$), while an ordinary substance melts at a higher temperature under a higher applied pressure (that is, $(dP/dT)_{\text{melting}} > 0$). Due to this difference a substance that melts at a temperature lower than the freezing point of an aqueous solution may melt at a temperature higher than the melting point of water at a sufficiently high applied pressure

When conventional methods are used, 5,000 gal. of feed (ice and organic liquid) have to be pumped through a high-pressure pump and 4,500 gal. of products have to be depressurized through a turbine to produce 1,000 gal. of water. The equipment therefore is very large and the energy consumption in this operation is in the order of 25 kw.-hr./1,000 gal. of fresh water produced.

When flow work exchangers are adopted, only 500 gal. of feed have to be pressurized through a high-pressure pump and no turbine is required. It is estimated that about a 50% reduction in equipment cost is obtained and the energy requirement is reduced to 15 kw.-hr./1,000 gal. of water produced.

Production of Phenol from Chlorobenzene

In the so-called caustic process (*7*), chlorobenzene, 10% diphenyl oxide, and a 10 to 15% aqueous caustic soda solution are introduced into a reactor maintained at 5,000 lb./sq.in. and 700°F. The product stream is depressurized. This is an example of high-pressure processes where high pressures are applied to maintain reactants and products under condensed state. When a flow work exchanger is used there is no need for the high-pressure pump and the turbine.

Hydrogenation of Organic Substances

Butanol can be manufactured by the high-pressure hydrogenation of aldol (*9*). Since the density of butanol is less than that of aldol, there is a volume expansion accompanying the process. Thus, it belongs to the type B process. When a flow work exchanger is used, neither the high-pressure pump nor the turbine will be required. Hydrogenation of coal also belongs to this category.

ACKNOWLEDGMENT

The authors are grateful for the facilities and assistance provided by the Department of Chemical Engineering and the Engineering Experiment Station of the Kansas State University in the preparation of the manuscripts. The authors appreciate the discussions and comments provided by the faculty members of the Department of Chemical Engineering of Kansas State University headed by Professor W. H. Honstead. Special thanks are due to Dr. Larry E. Erickson of Kansas State University for helpful comments. Thanks are also due to Professors Takeichiro Takamatsu of Kyoto University and Shoji Makishima of Tokyo University, Japan, for their advice.

Optimization studies of desalination processes by adopting flow work exchangers to the desalination processes have been supported by the Office of Saline Water, Department of the Interior. We gratefully acknowledge this support.

NOTATION

J_1, J_2, J_3 = pumps
P = pressure
P_H = pressure at the high-pressure side
P_L = pressure at the low-pressure side
PV = flow work
V = volume
V_F = volume of feed fluid
V_P = volume of product fluid
$V_1, V_2, \ldots V_7, V_8$ = valves
$-w_f$ = shaft work for flow process
$-w_{nf}$ = shaft work for nonflow process
η_m = motor efficiency
η_p = pump efficiency
η_t = turbine efficiency

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Manuscript received May 6, 1966; revision received August 1, 1966; paper accepted August 1, 1966.