US007328591B2

(12) **United States Patent**
Holtzapple et al.

(10) **Patent No.: US 7,328,591 B2**
(45) **Date of Patent: Feb. 12, 2008**

(54) **JET EJECTOR SYSTEM AND METHOD**

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(73) Assignees: **The Texas A&M University System**, College Station, TX (US); **StarRotor Corporation**, College Station, TX (US); **Highland Interests, Inc.**, Bryan, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 475 days.

(21) Appl. No.: **10/944,071**

(22) Filed: **Sep. 17, 2004**

(65) **Prior Publication Data**

US 2005/0063832 A1 Mar. 24, 2005

Related U.S. Application Data

(60) Provisional application No. 60/504,138, filed on Sep. 19, 2003.

(51) **Int. Cl.**
F25D 23/12 (2006.01)

(52) **U.S. Cl.** **62/333**; 62/498

(58) **Field of Classification Search** 62/331, 62/333, 498; 202/155, 174; 417/76, 151
See application file for complete search history.

(56) **References Cited**

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PCt Invitation to Pay Additional Fees for International Application No. PCt/US2004/030615, filed Sep. 20, 2004. (6 pages), Jan. 28, 2005.

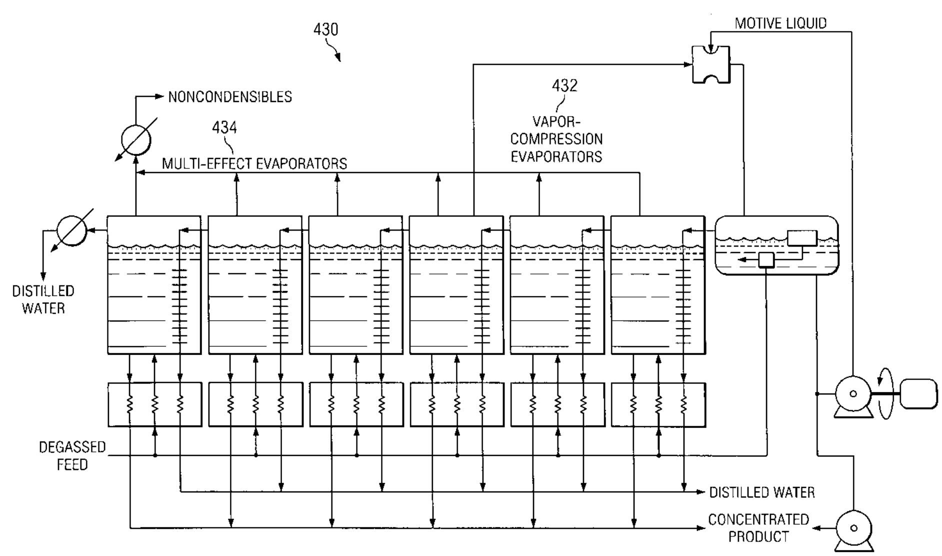
(Continued)

Primary Examiner—Melvin Jones
(74) *Attorney, Agent, or Firm*—Baker Botts L.L.P.

(57) **ABSTRACT**

According to one embodiment of the invention, a jet ejector method includes providing a primary jet ejector having a primary inlet stream, coupling one or more secondary jet ejectors to the primary jet ejector such that all of the jet ejectors are in a cascaded arrangement, bleeding off a portion of the primary inlet stream and directing the portion of the primary inlet stream to the secondary jet ejector that is closest to the primary jet ejector in the cascaded arrangement, and directing a motive fluid into the secondary jet ejector that is farthest from the primary jet ejector in the cascaded arrangement. The method further includes, at each secondary jet ejector, receiving at least some of the portion of the primary inlet stream and at least some of the motive fluid to create respective mixtures within the secondary jet ejectors, and at each secondary jet ejector, directing at least a portion of the respective mixture to adjacent jet ejectors in the cascaded arrangement.

24 Claims, 39 Drawing Sheets



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Notification of Transmittal of the International Search Report and Written Opinion of the Internatinal Searching Authority for International Application No. PCT/US2004/030660 filed Sep. 20, 2004. (15 pages), Jan. 14, 2005.

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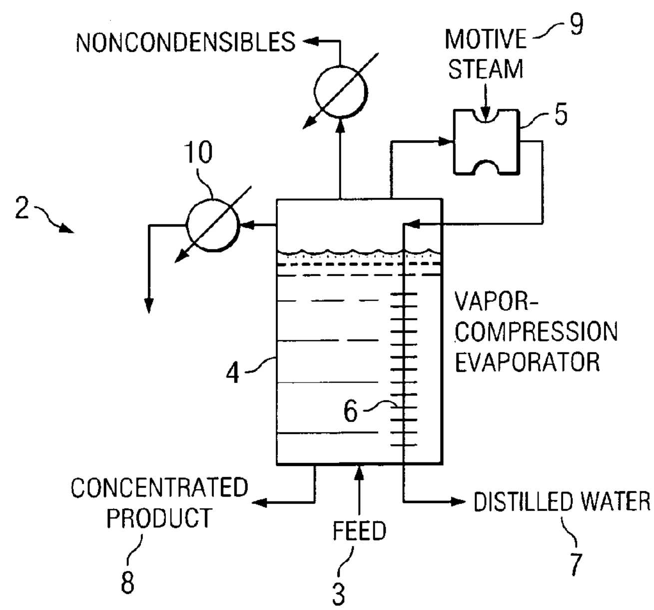
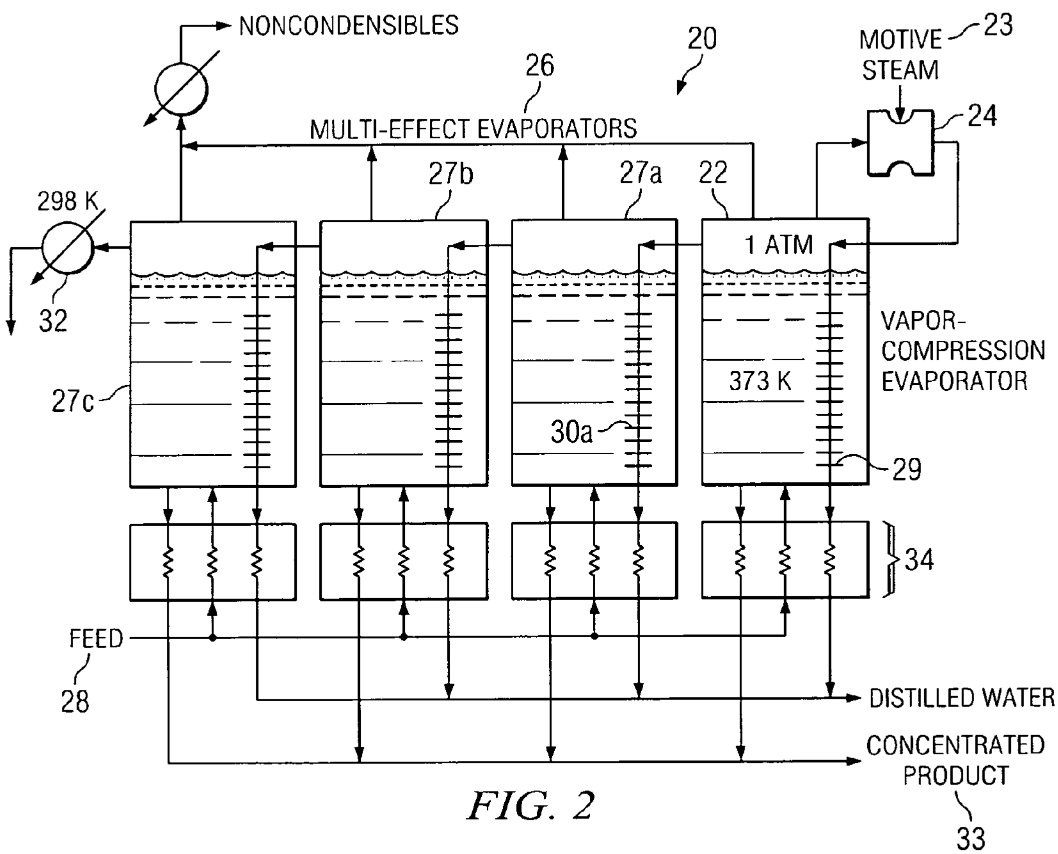


NONCONDENSIBLES
MOTIVE STEAM
9
5
10
2
VAPOR-COMPRESSION EVAPORATOR
4
6
CONCENTRATED PRODUCT
8
FEED
3
DISTILLED WATER
7

FIG. 1



NONCONDENSIBLES
20
MOTIVE STEAM
23
26
MULTI-EFFECT EVAPORATORS
24
298 K
27b
27a
22
1 ATM
32
VAPOR-COMPRESSION EVAPORATOR
373 K
27c
30a
29
34
FEED
28
DISTILLED WATER
CONCENTRATED PRODUCT
33

FIG. 2

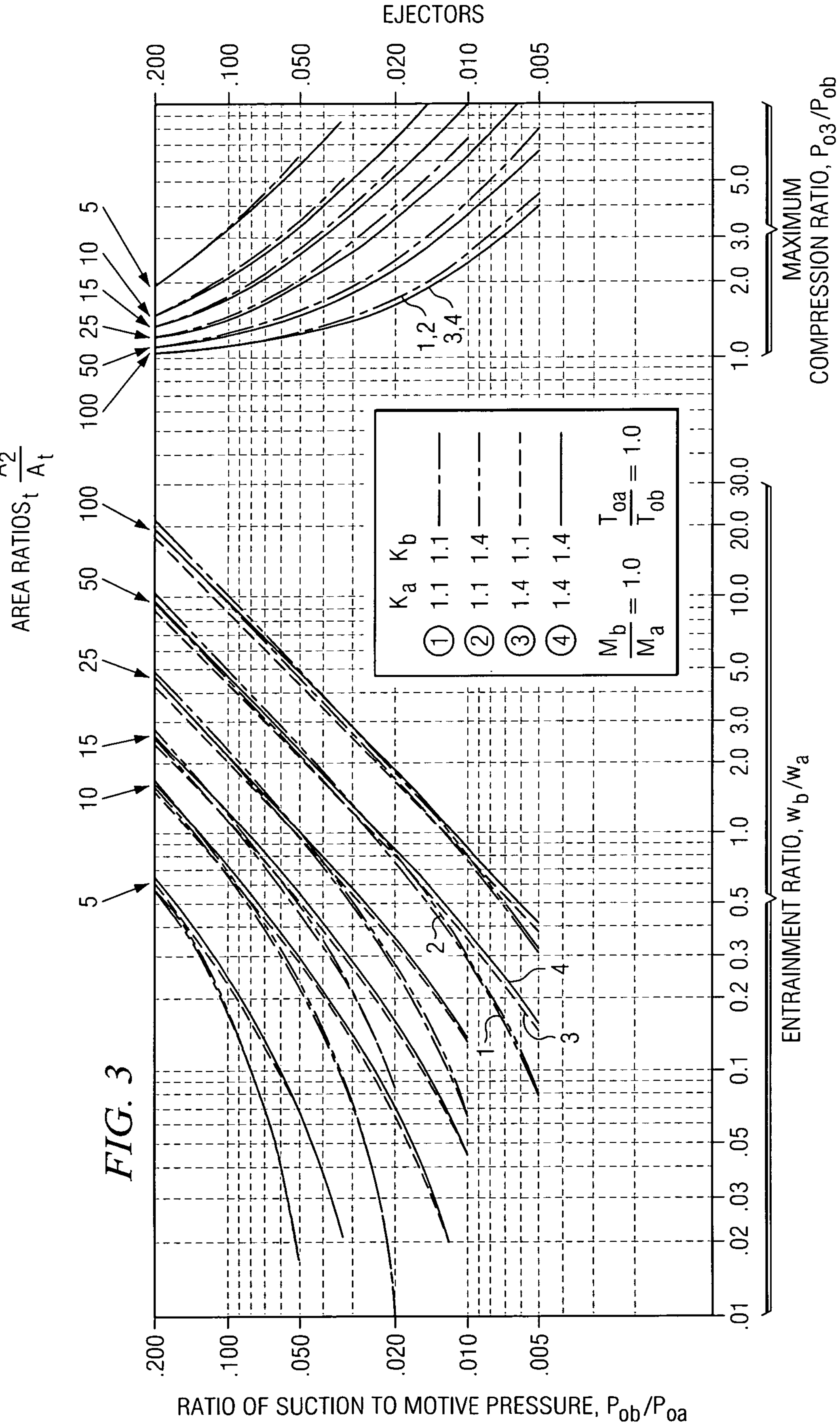

EJECTORS
AREA RATIOS
MAXIMUM COMPRESSION RATIO, P03/Pob
ENTRAINMENT RATIO, wb/wa
RATIO OF SUCTION TO MOTIVE PRESSURE, Pob/Poa
Ka Kb
1 1.1 1.1
2 1.1 1.4
3 1.4 1.1
4 1.4 1.4
Mb/Ma = 1.0 Toa/Tob = 1.0

FIG. 3

FIG. 4

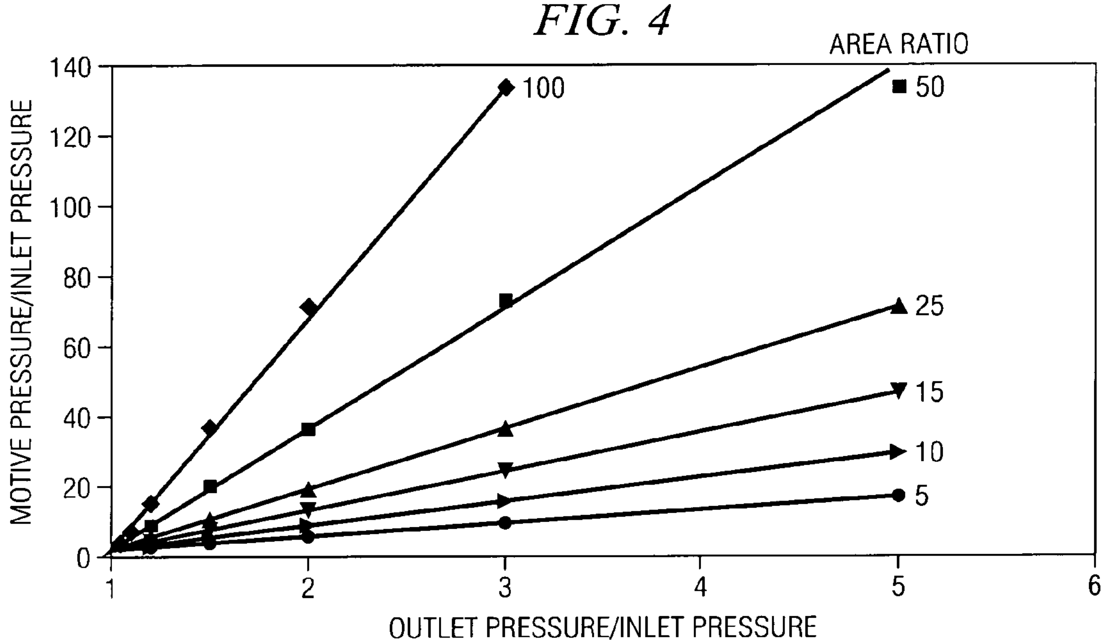

AREA RATIO
140
120
100
80
60
40
20
0
MOTIVE PRESSURE/INLET PRESSURE
100
50
25
15
10
5
1
2
3
4
5
6
OUTLET PRESSURE/INLET PRESSURE

FIG. 5

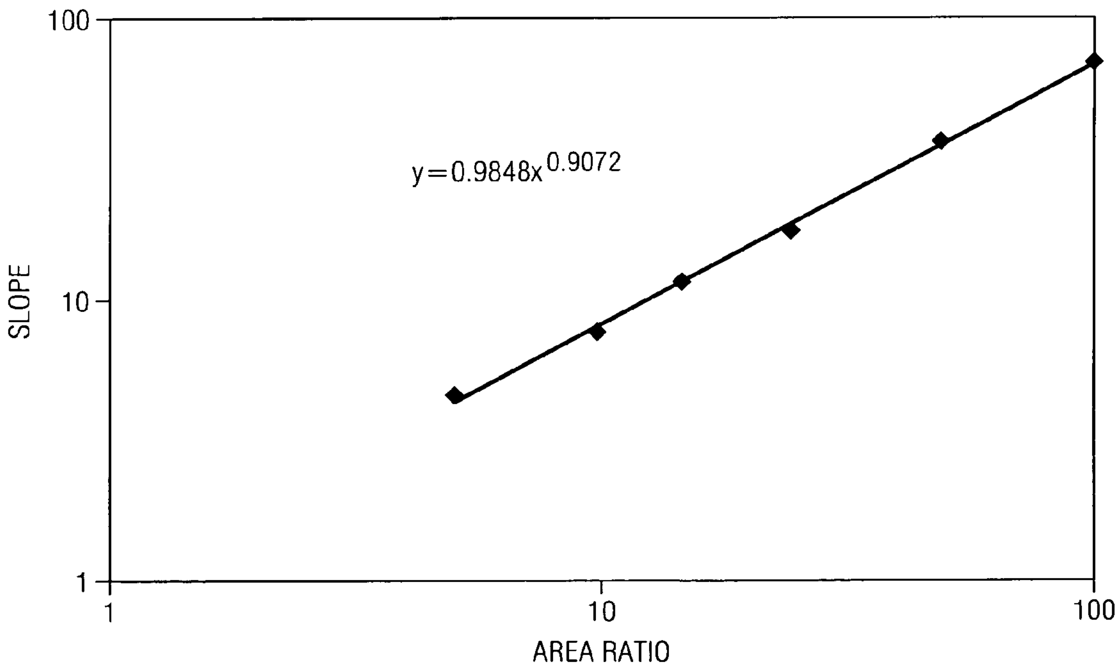

100
10
1
SLOPE
y=0.9848x^0.9072
1
10
100
AREA RATIO

FIG. 6

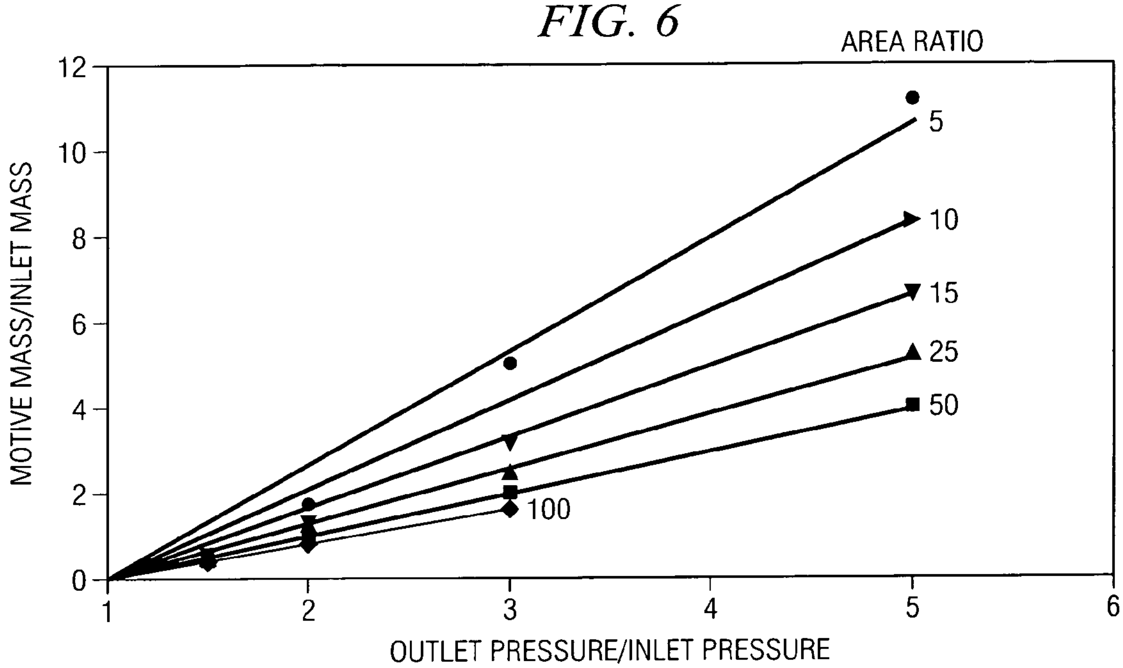
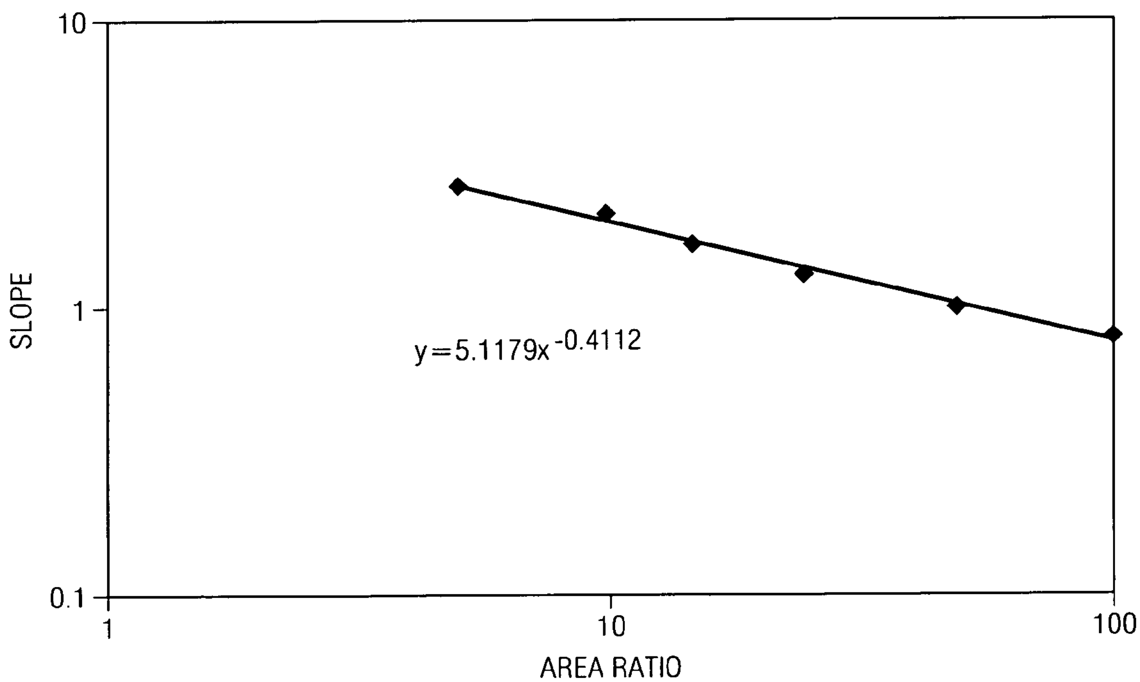

AREA RATIO
12
10
8
6
4
2
0
MOTIVE MASS/INLET MASS
5
10
15
25
50
100
1
2
3
4
5
6
OUTLET PRESSURE/INLET PRESSURE

FIG. 7


10
1
0.1
SLOPE
y=5.1179x^-0.4112
1
10
100
AREA RATIO

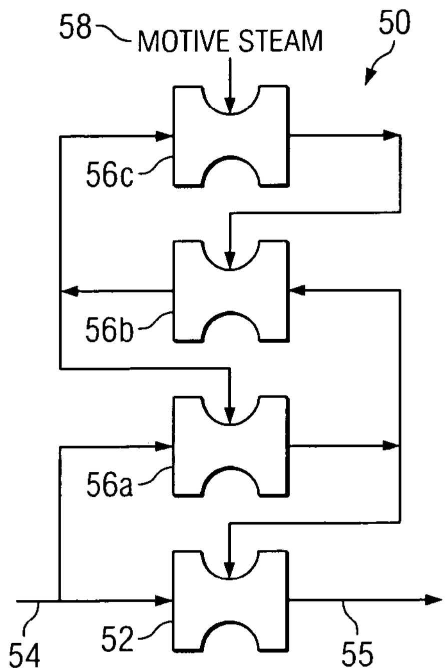


FIG. 8

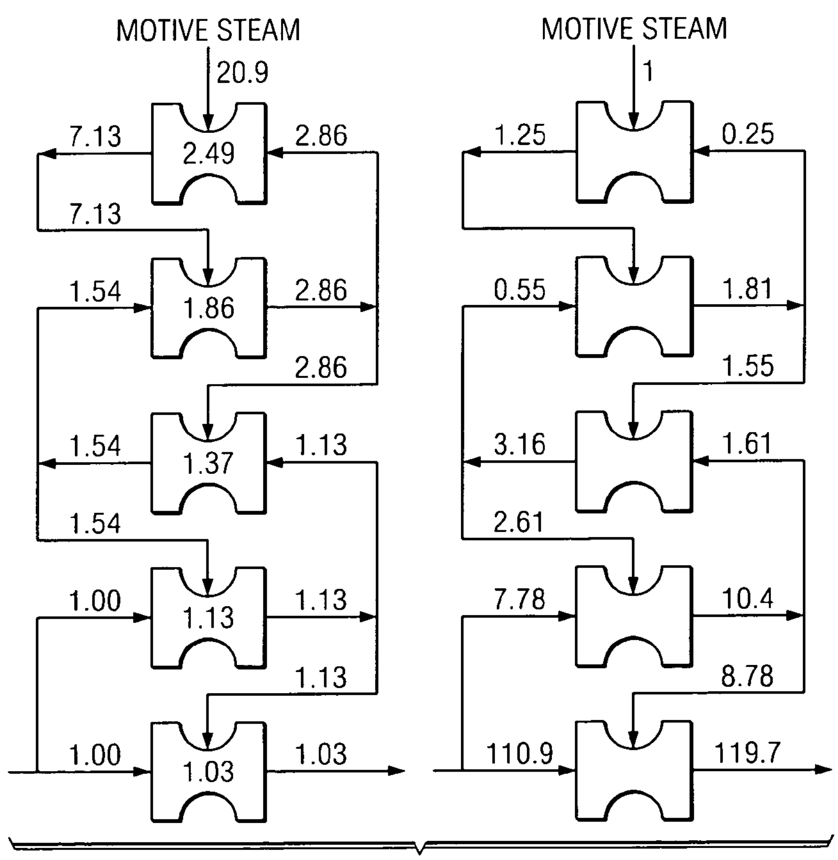


FIG. 9
(AR=5)

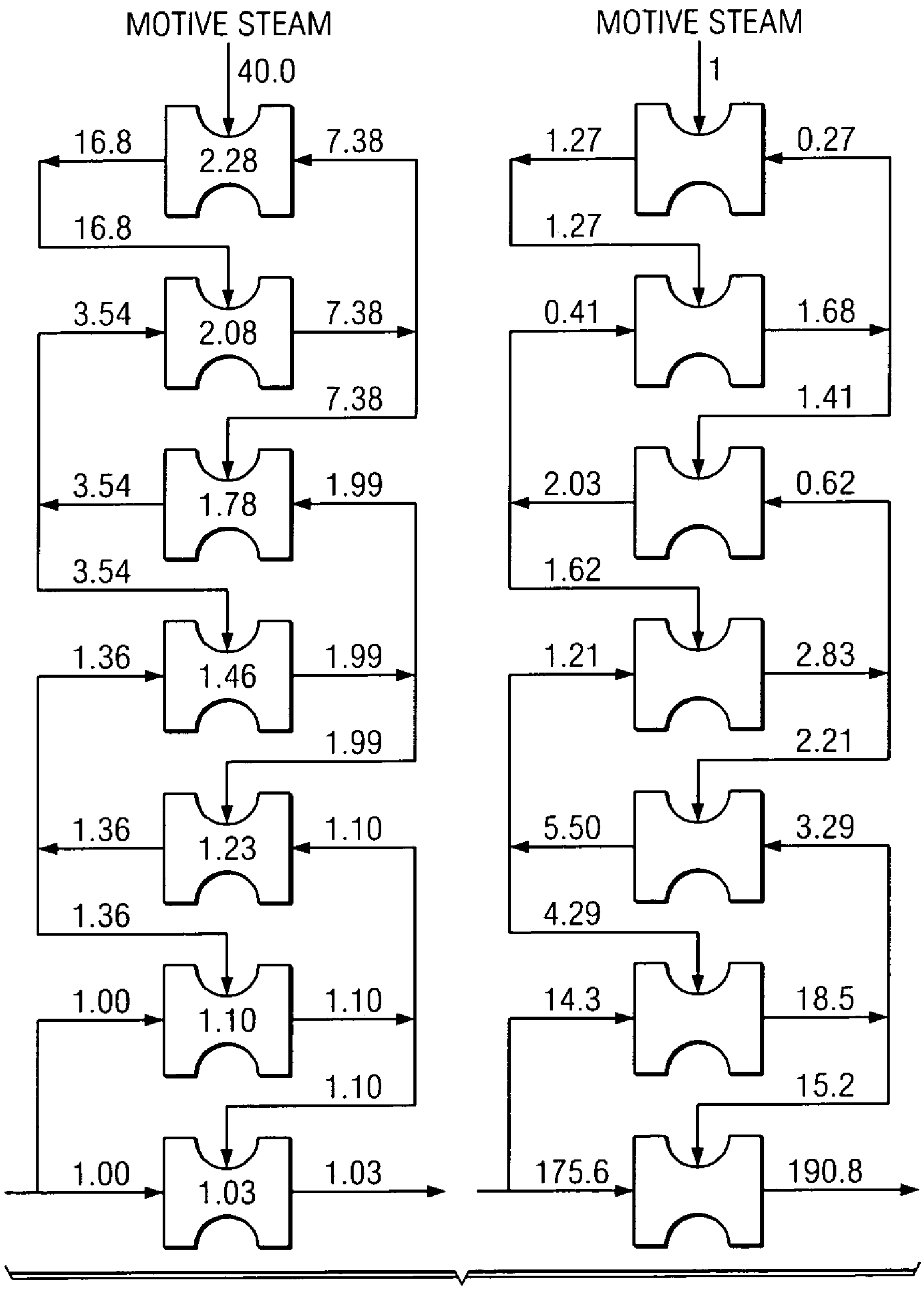

MOTIVE STEAM
40.0
16.8
2.28
7.38
16.8
3.54
2.08
7.38
7.38
3.54
1.78
1.99
3.54
1.36
1.46
1.99
1.99
1.36
1.23
1.10
1.36
1.00
1.10
1.10
1.10
1.00
1.03
1.03
MOTIVE STEAM
1
1.27
0.27
1.27
0.41
1.68
1.41
2.03
0.62
1.62
1.21
2.83
2.21
5.50
3.29
4.29
14.3
18.5
15.2
175.6
190.8

FIG. 10

(AR=4)

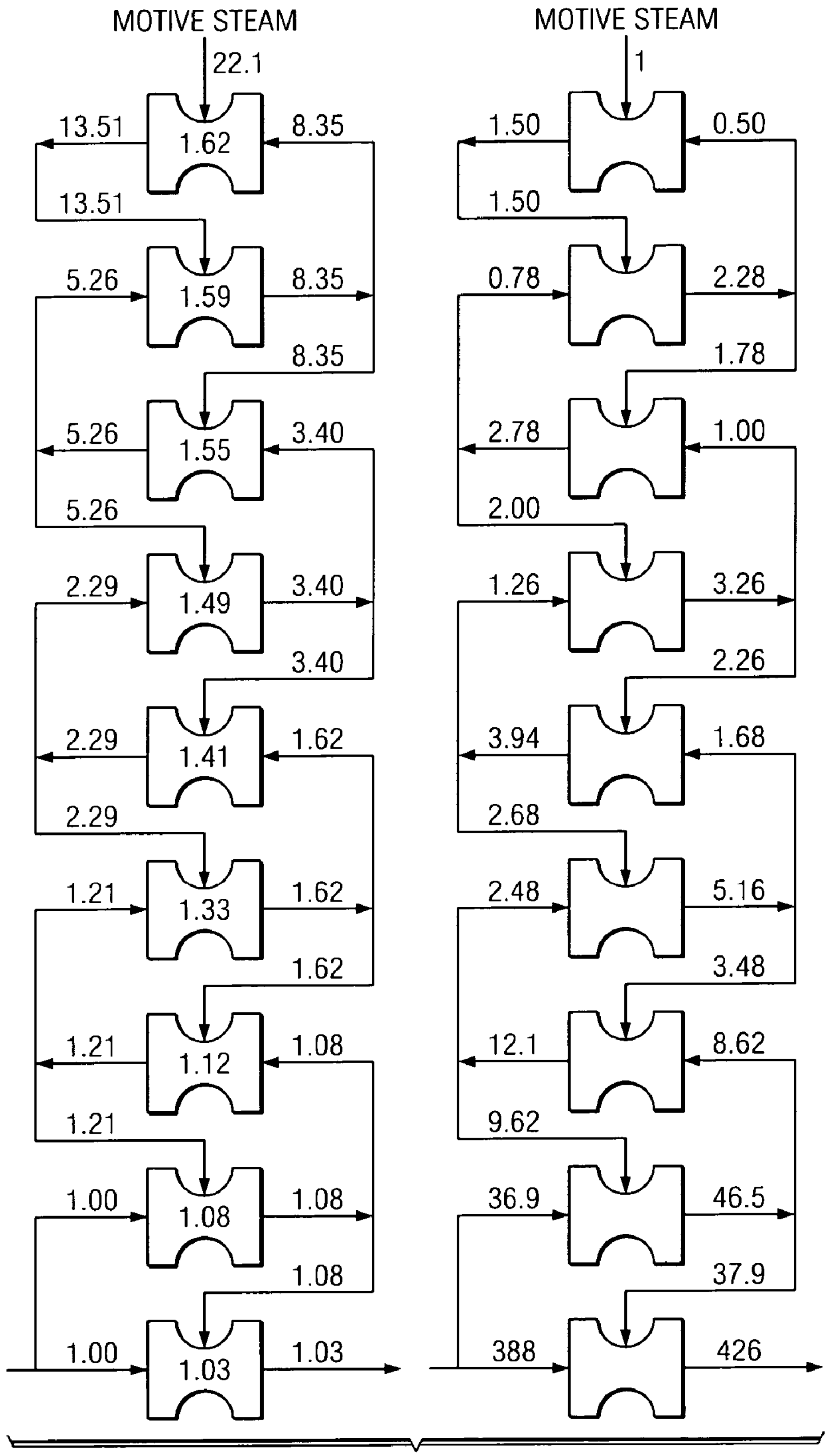

MOTIVE STEAM
22.1
13.51
1.62
8.35
13.51
5.26
1.59
8.35
8.35
5.26
1.55
3.40
5.26
2.29
1.49
3.40
3.40
2.29
1.41
1.62
2.29
1.21
1.33
1.62
1.62
1.21
1.12
1.08
1.21
1.00
1.08
1.08
1.08
1.00
1.03
1.03
MOTIVE STEAM
1
1.50
0.50
1.50
0.78
2.28
1.78
2.78
1.00
2.00
1.26
3.26
2.26
3.94
1.68
2.68
2.48
5.16
3.48
12.1
8.62
9.62
36.9
46.5
37.9
388
426

FIG. 11

(AR=3)

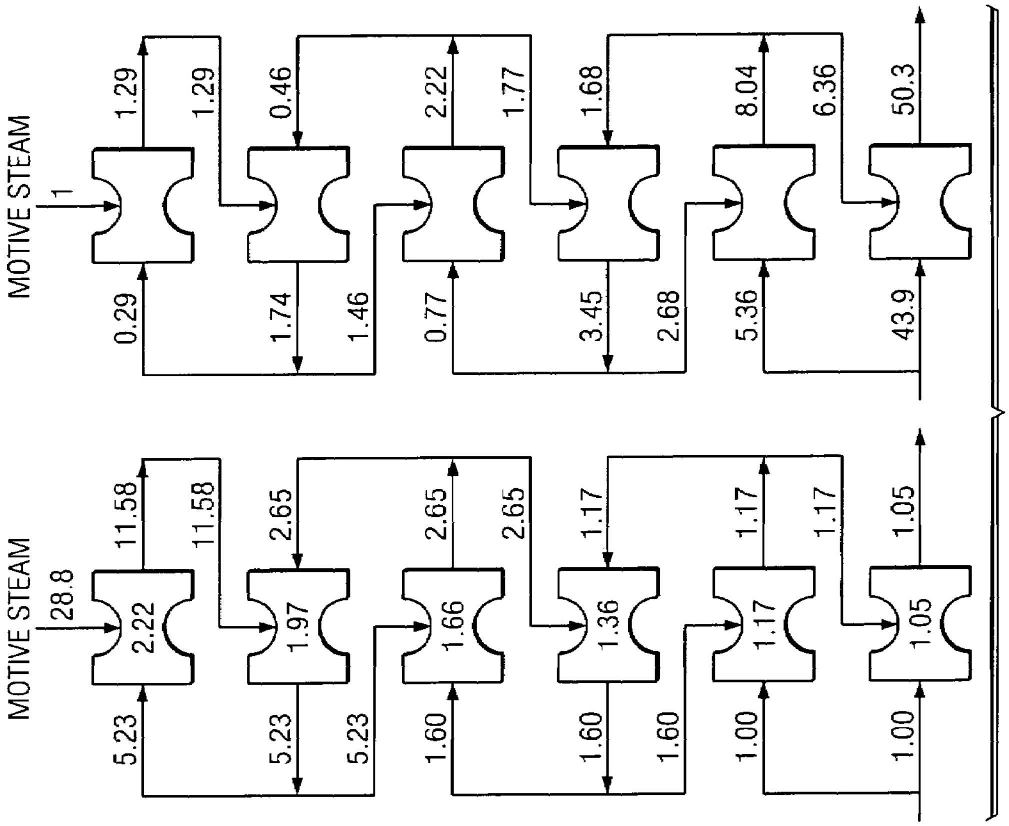


FIG. 13
(AR=4)

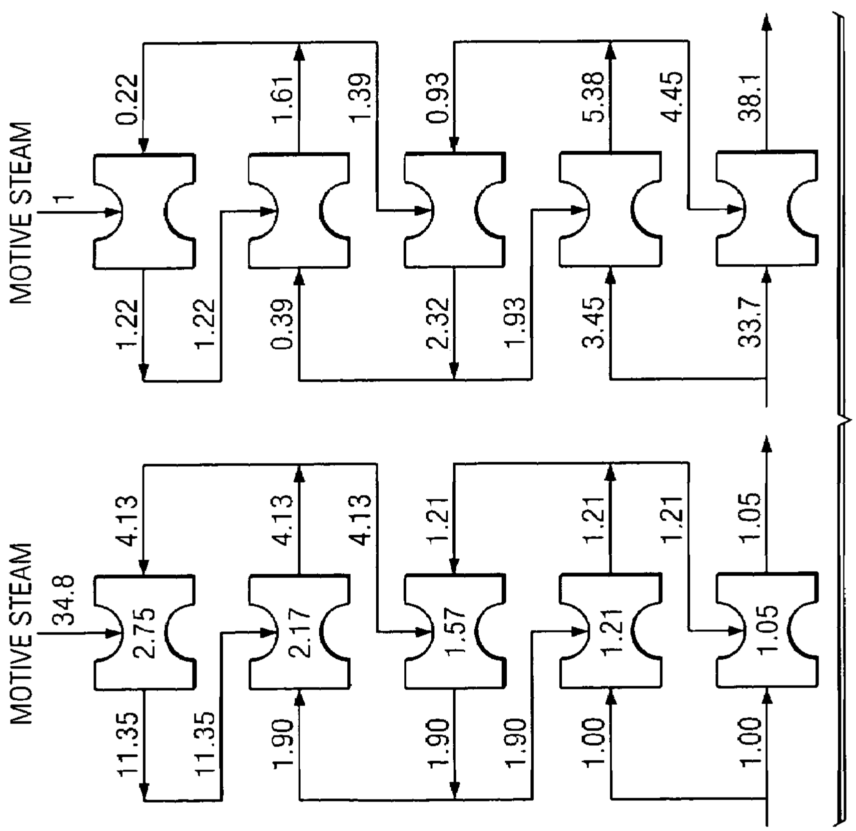


FIG. 12
(AR=5)

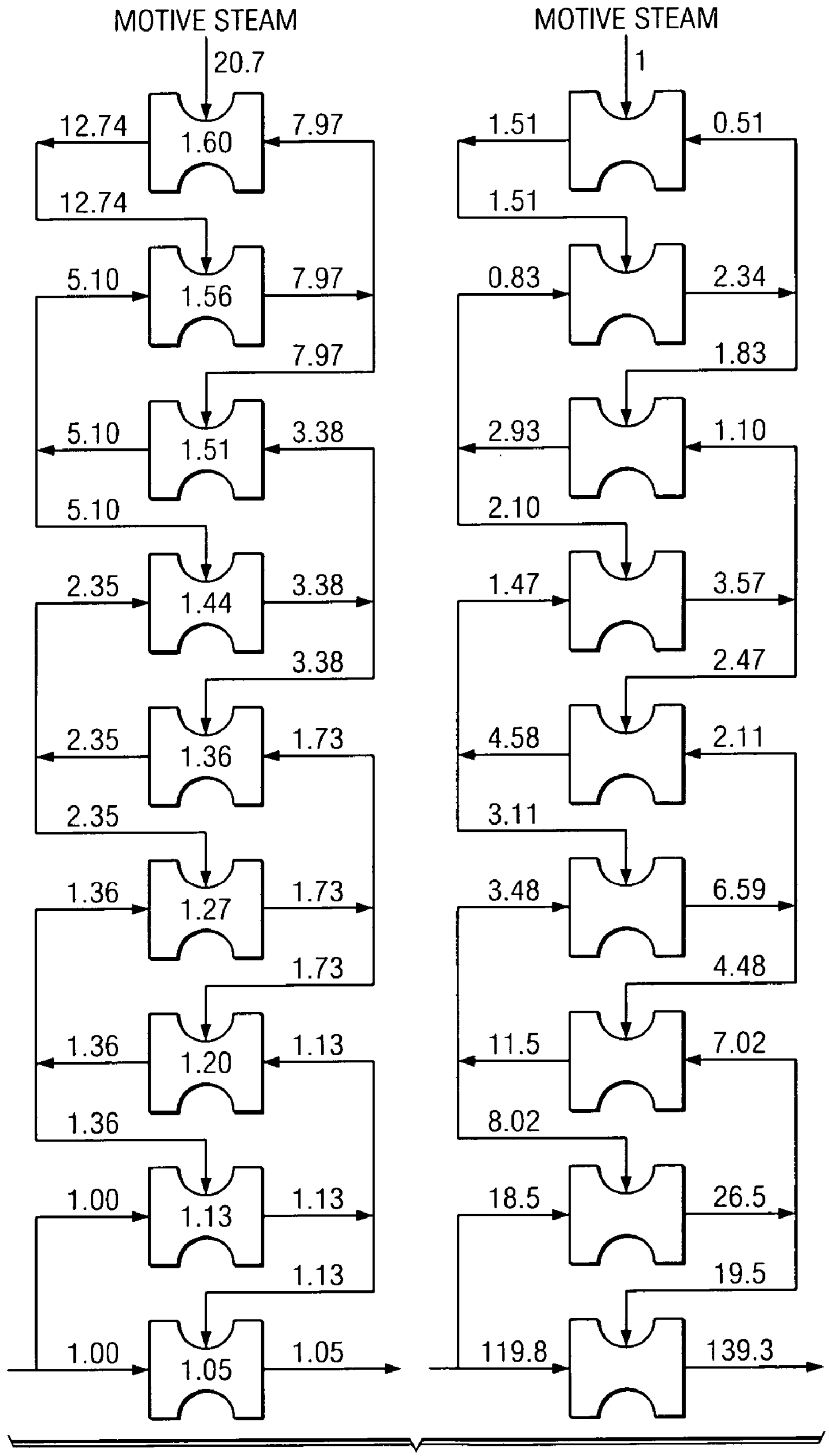

MOTIVE STEAM
20.7
12.74
1.60
7.97
12.74
5.10
1.56
7.97
7.97
5.10
1.51
3.38
5.10
2.35
1.44
3.38
3.38
2.35
1.36
1.73
2.35
1.36
1.27
1.73
1.73
1.36
1.20
1.13
1.36
1.00
1.13
1.13
1.13
1.00
1.05
1.05
MOTIVE STEAM
1
1.51
0.51
1.51
0.83
2.34
1.83
2.93
1.10
2.10
1.47
3.57
2.47
4.58
2.11
3.11
3.48
6.59
4.48
11.5
7.02
8.02
18.5
26.5
19.5
119.8
139.3

FIG. 14
(AR=3)

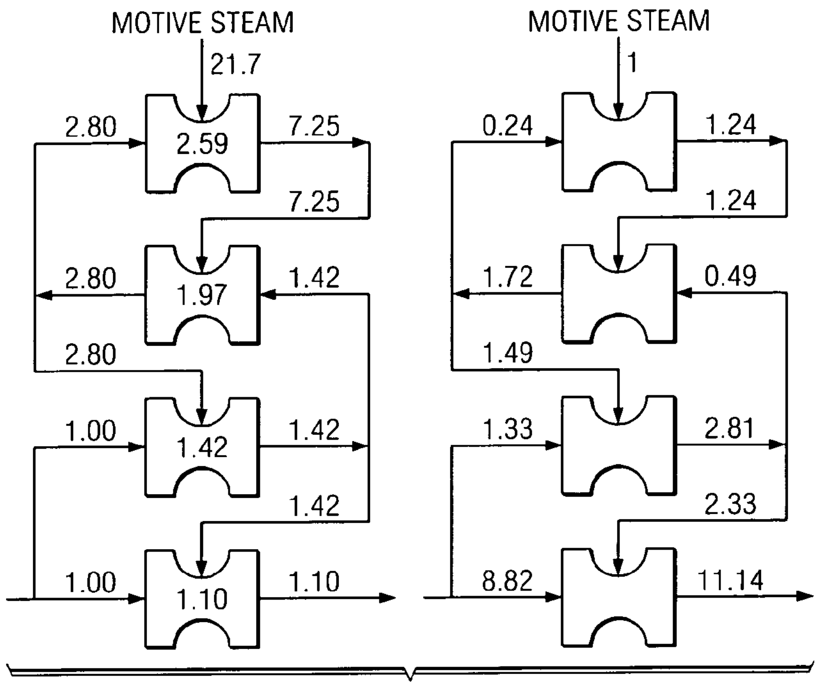


FIG. 15
(AR=5)

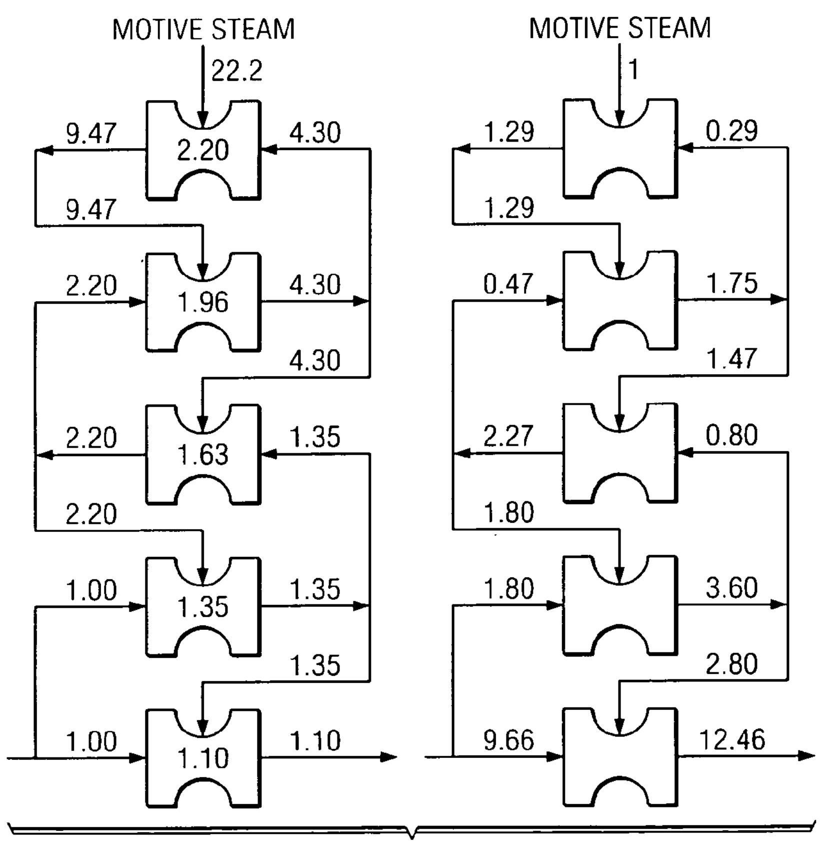


FIG. 16
(AR=4)

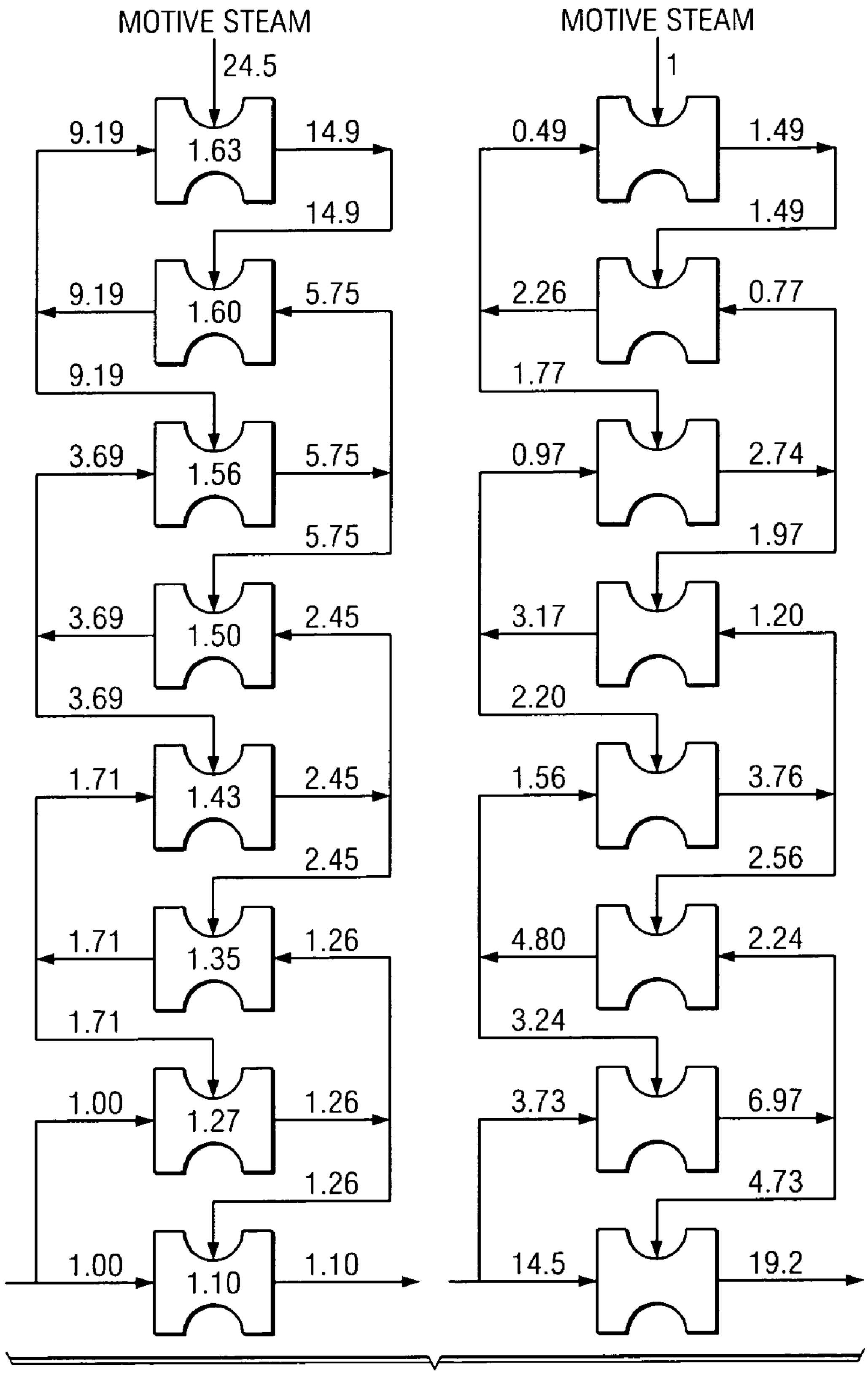

MOTIVE STEAM
24.5
9.19
1.63
14.9
14.9
9.19
1.60
5.75
9.19
3.69
1.56
5.75
5.75
3.69
1.50
2.45
3.69
1.71
1.43
2.45
2.45
1.71
1.35
1.26
1.71
1.00
1.27
1.26
1.26
1.00
1.10
1.10
MOTIVE STEAM
1
0.49
1.49
1.49
2.26
0.77
1.77
0.97
2.74
1.97
3.17
1.20
2.20
1.56
3.76
2.56
4.80
2.24
3.24
3.73
6.97
4.73
14.5
19.2

FIG. 17
(AR=3)

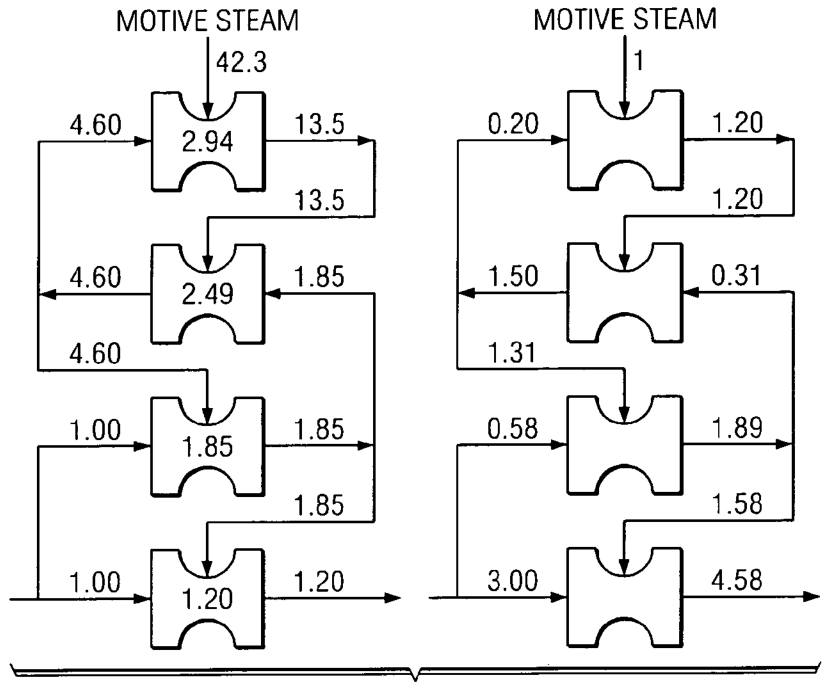


FIG. 18
(AR=5)

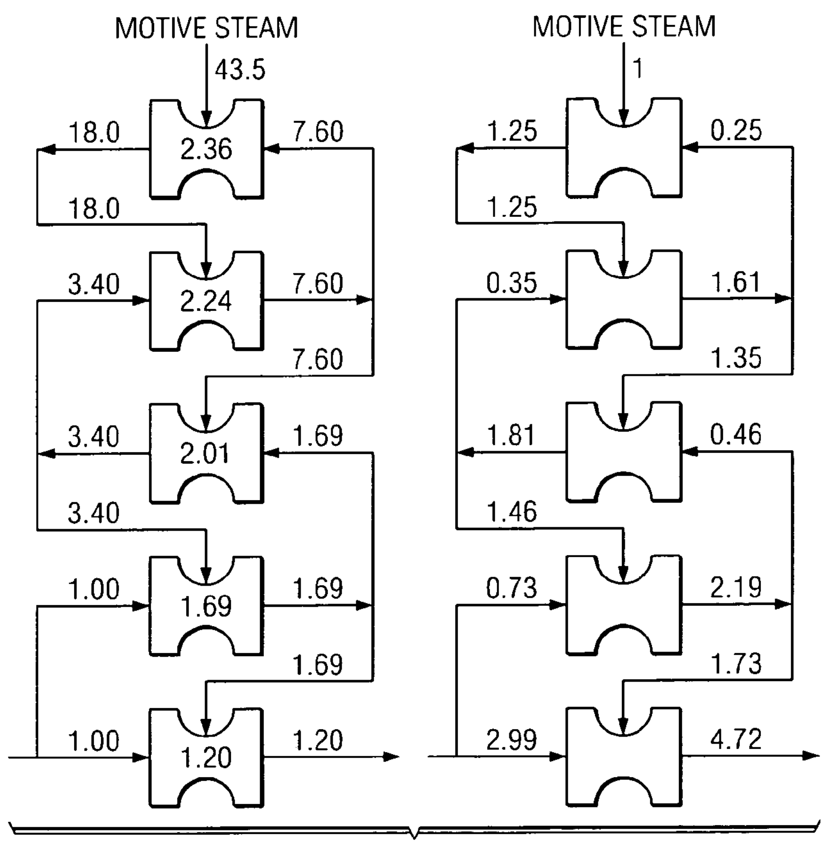


FIG. 19
(AR=4)

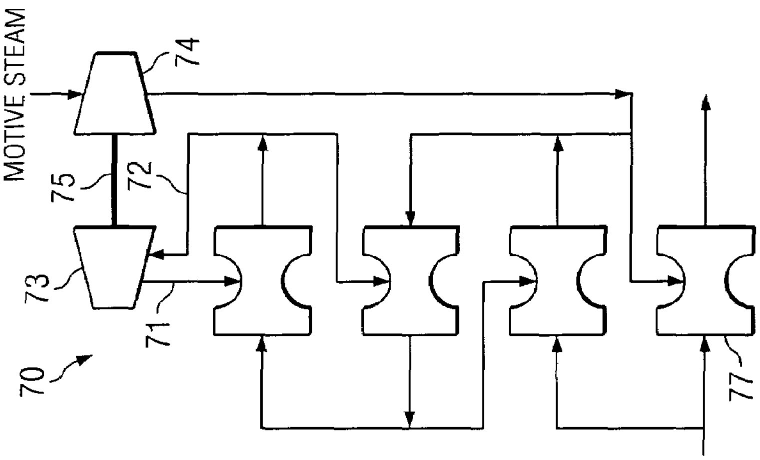


FIG. 22

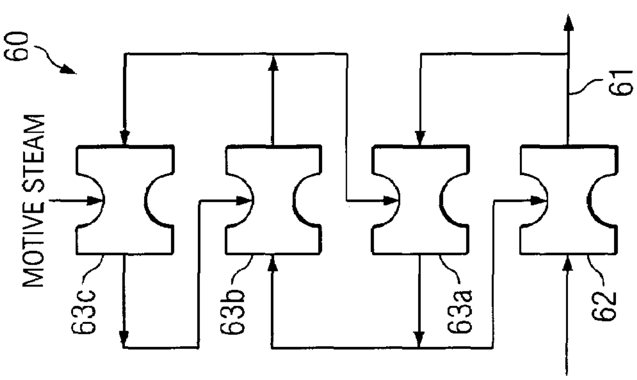


FIG. 21

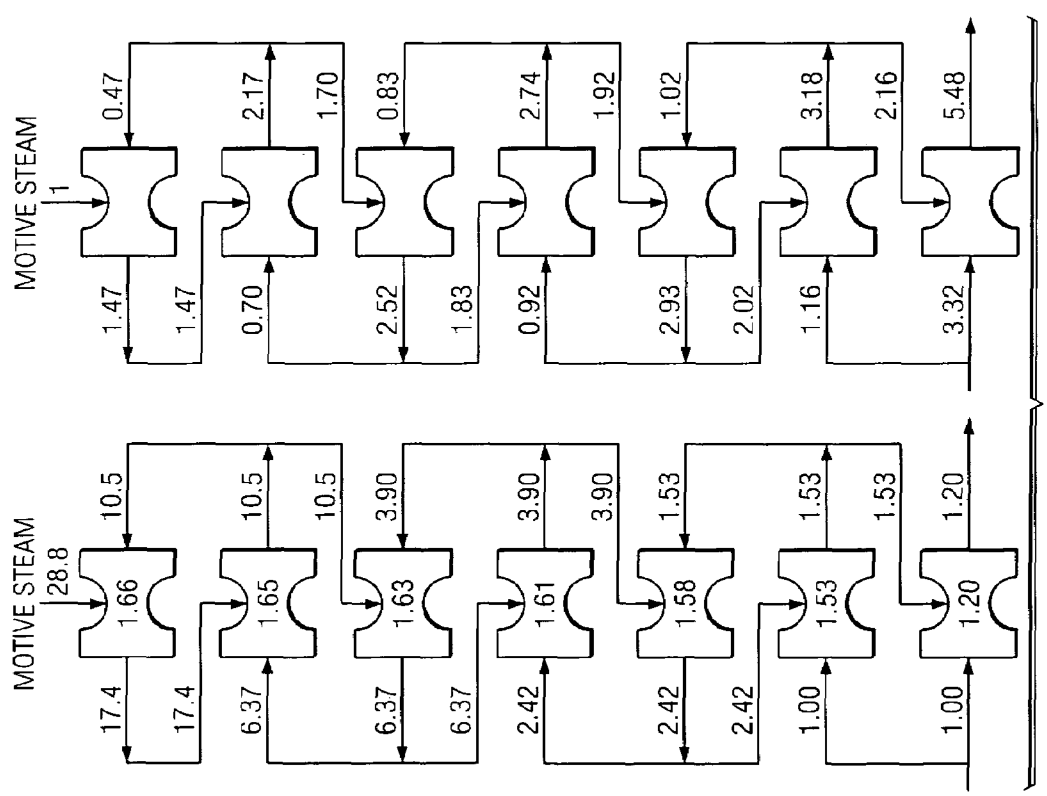


FIG. 20
(AR=3)

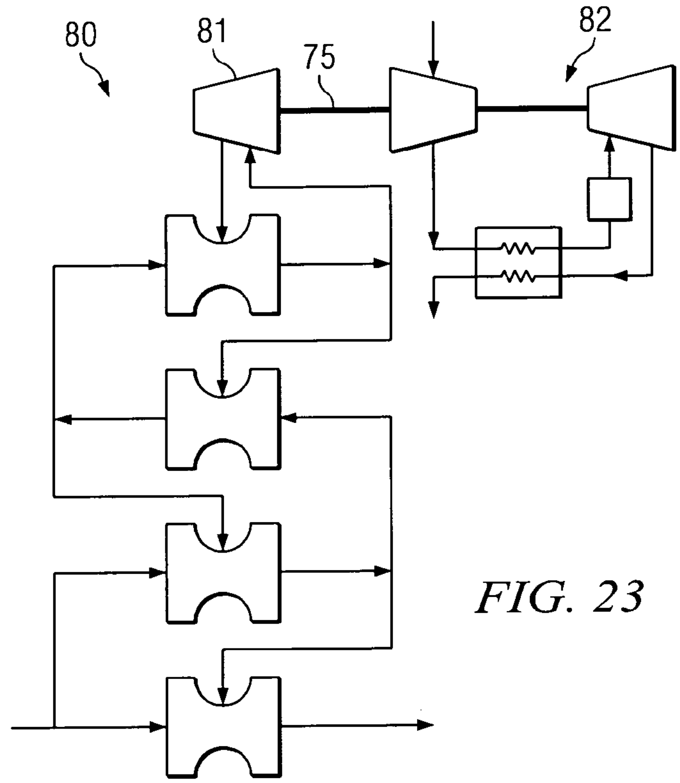

80
81
75
82

FIG. 23

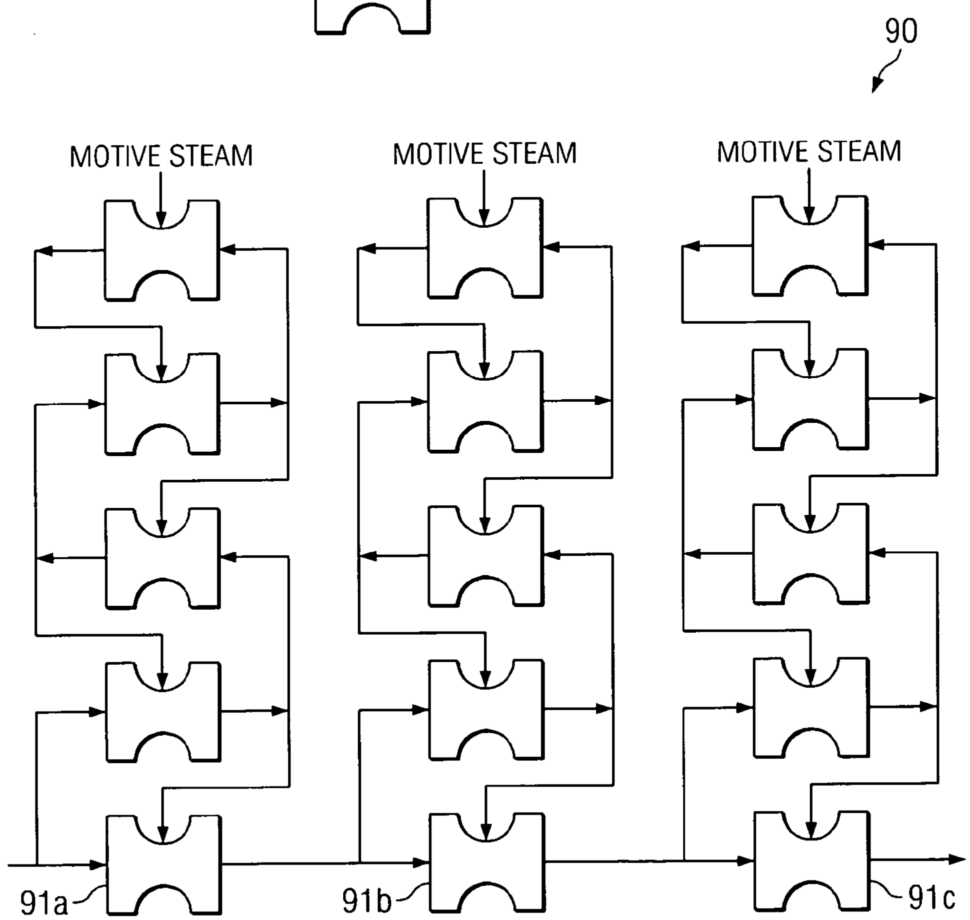

90
MOTIVE STEAM
MOTIVE STEAM
MOTIVE STEAM
91a
91b
91c

FIG. 24

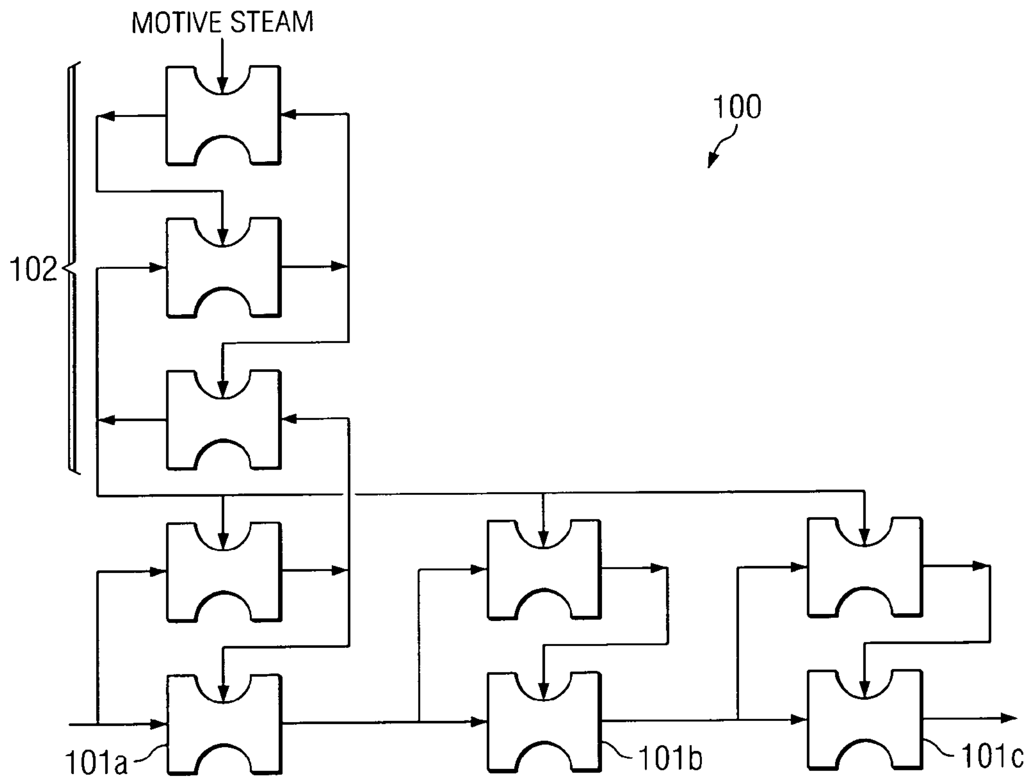

MOTIVE STEAM
100
102
101a
101b
101c

FIG. 25

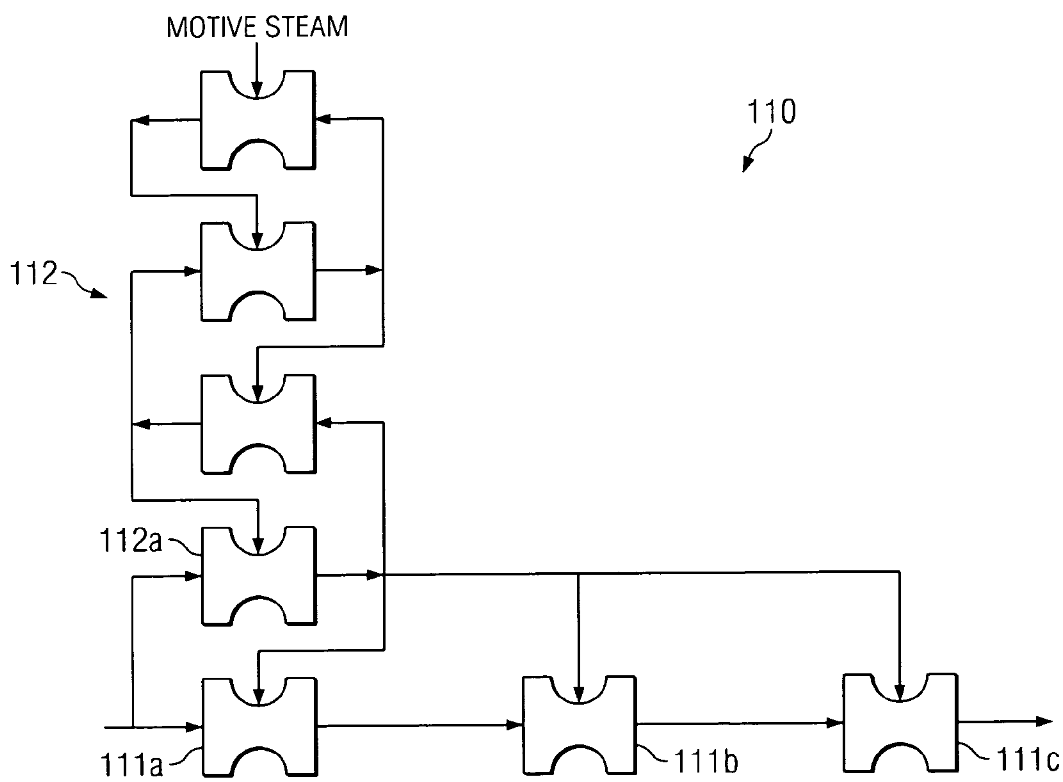
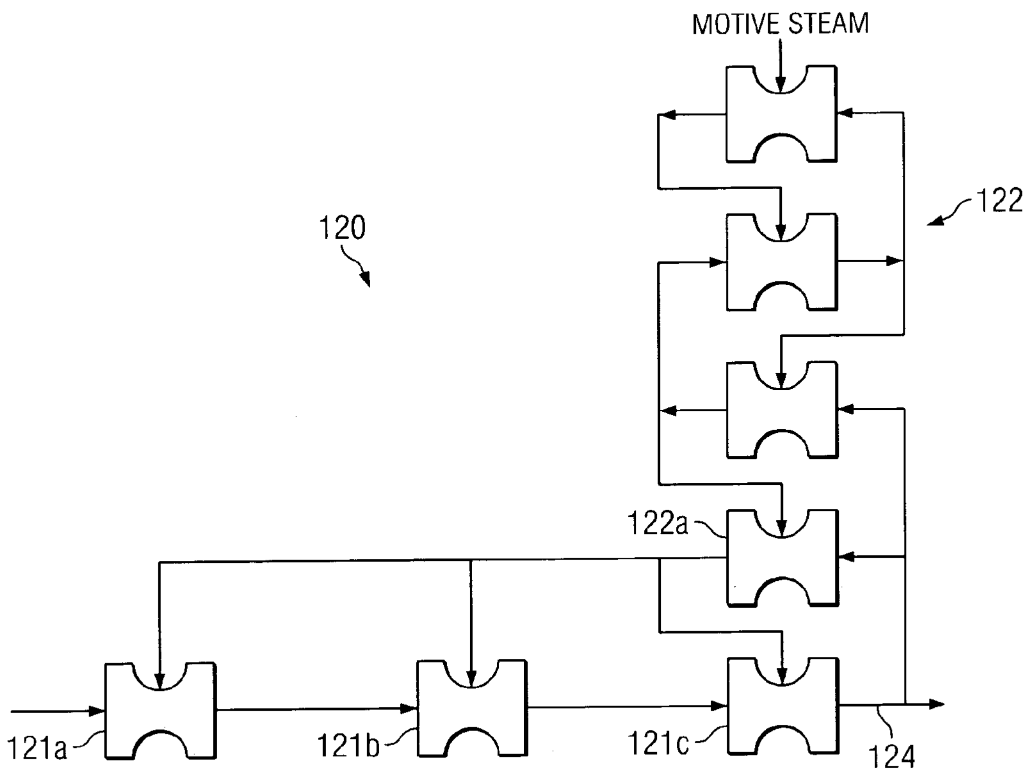
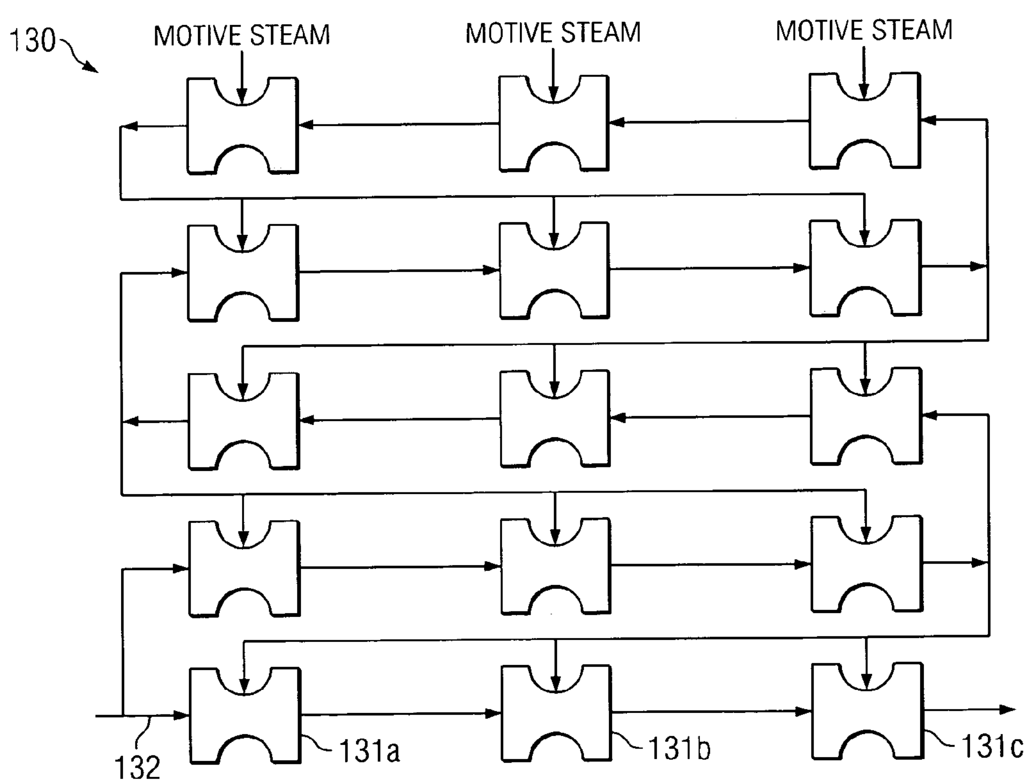

MOTIVE STEAM
110
112
112a
111a
111b
111c

FIG. 26



MOTIVE STEAM
122
120
122a
121a
121b
121c
124

FIG. 27



130
MOTIVE STEAM
MOTIVE STEAM
MOTIVE STEAM
132
131a
131b
131c

FIG. 28

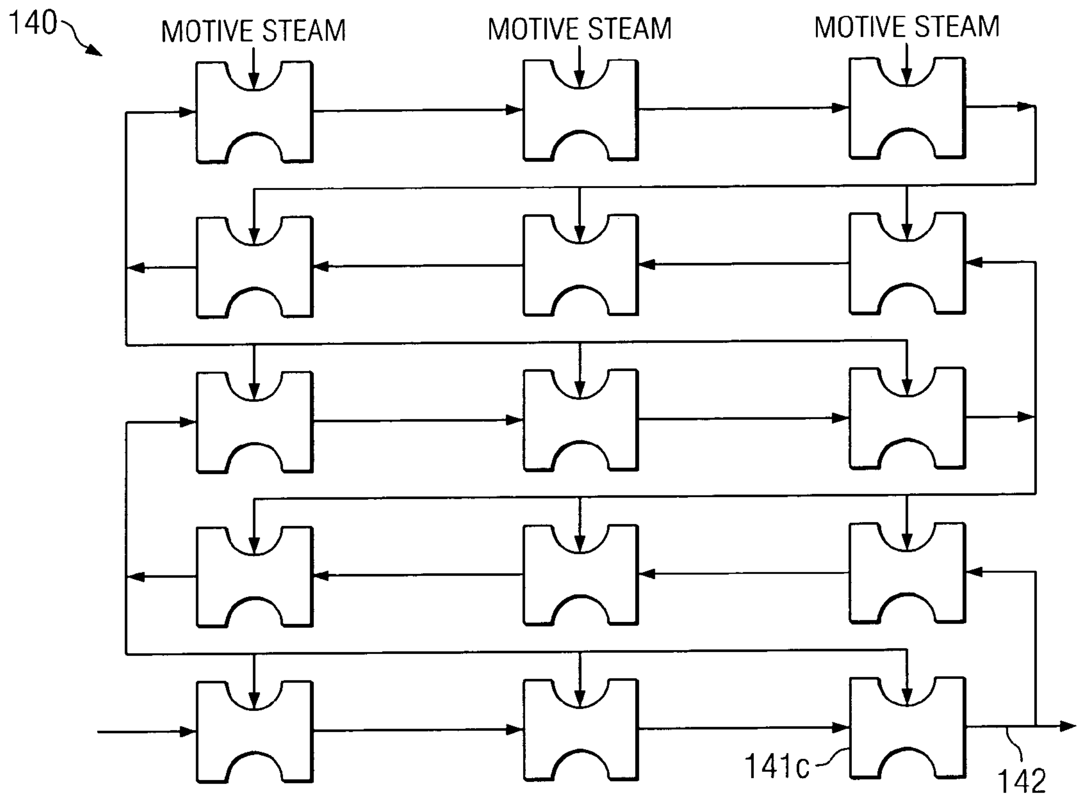

140
MOTIVE STEAM
MOTIVE STEAM
MOTIVE STEAM
141c
142

FIG. 29

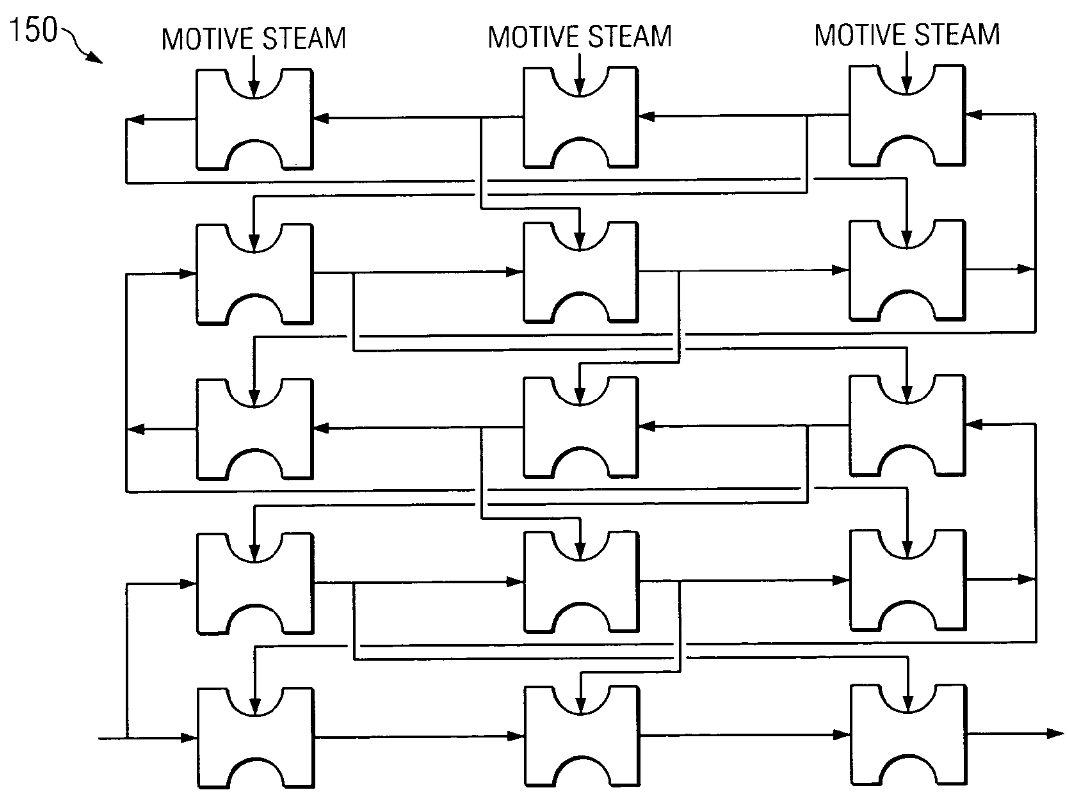

150
MOTIVE STEAM
MOTIVE STEAM
MOTIVE STEAM

FIG. 30

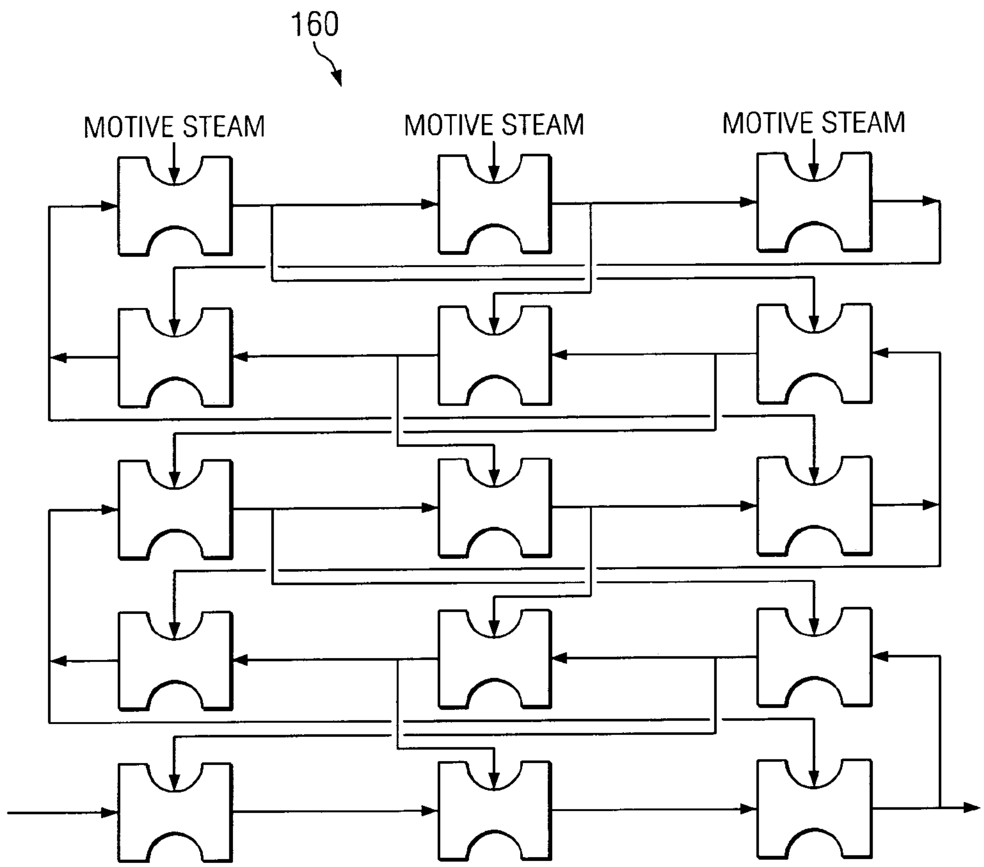

160
MOTIVE STEAM
MOTIVE STEAM
MOTIVE STEAM

FIG. 31

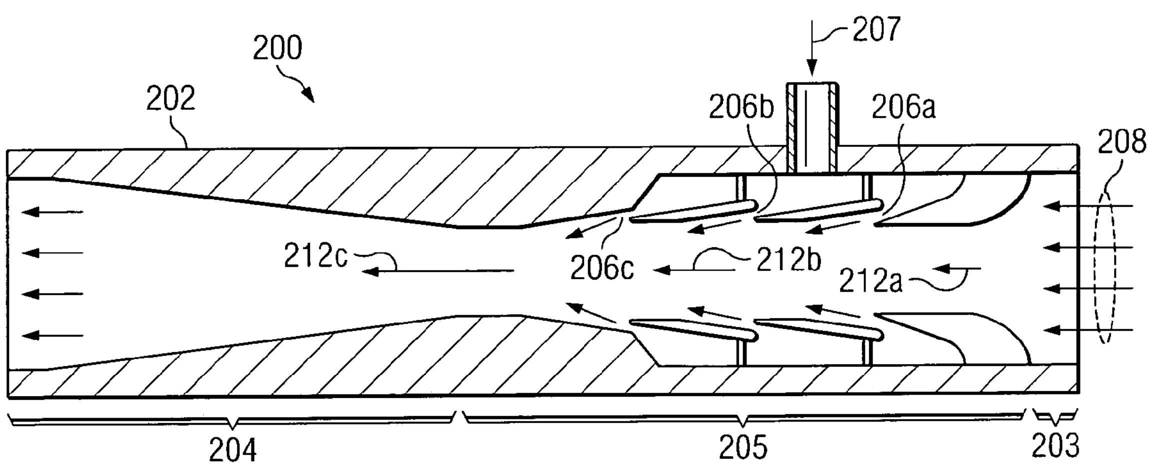

207
200
202
206b
206a
208
212c
206c
212b
212a
204
205
203

FIG. 32

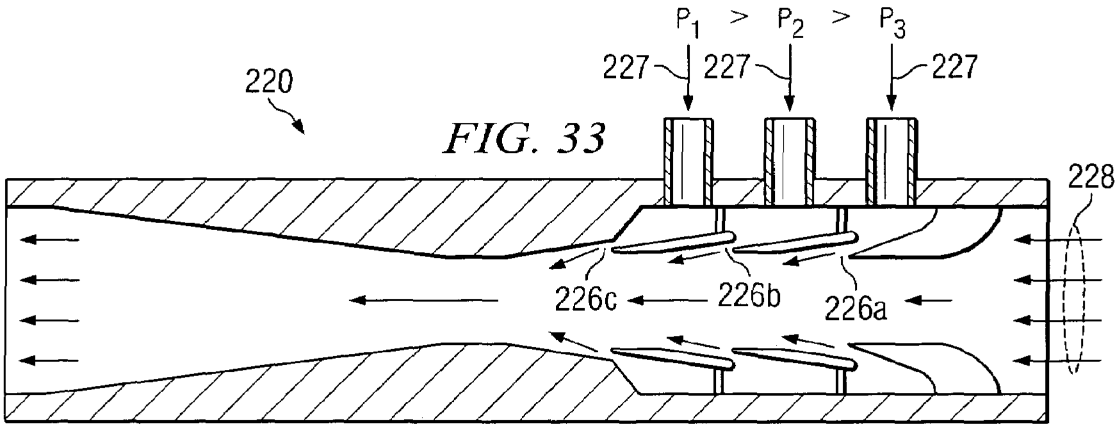


FIG. 33

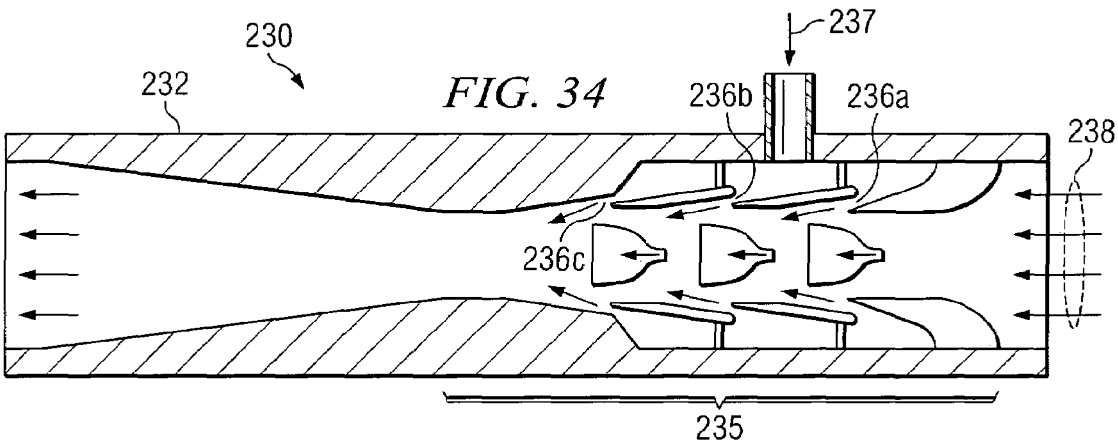


FIG. 34

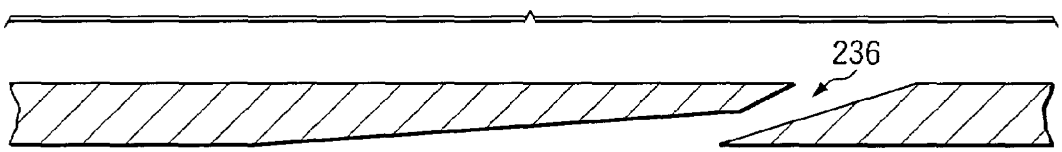


FIG. 35A

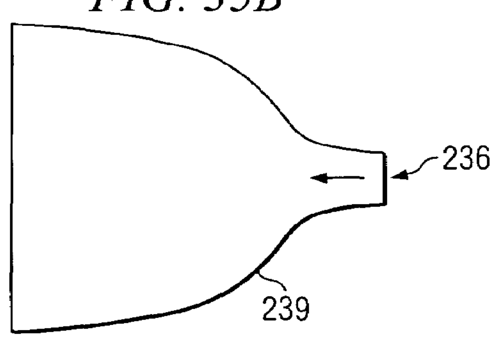


FIG. 35B

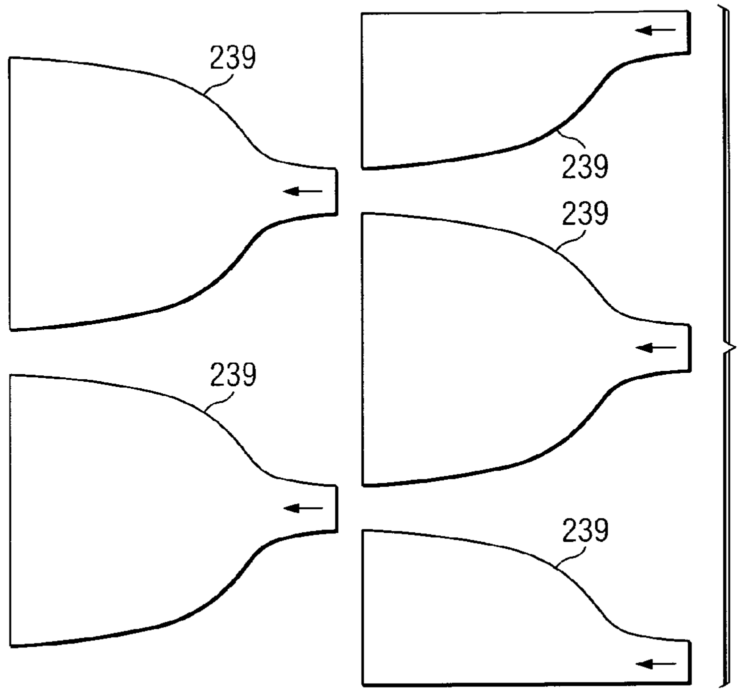


FIG. 36

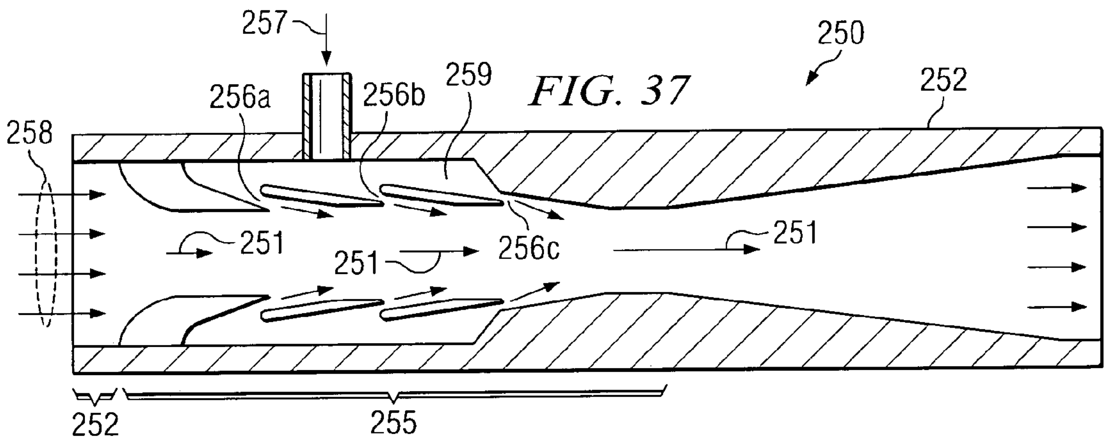


FIG. 37

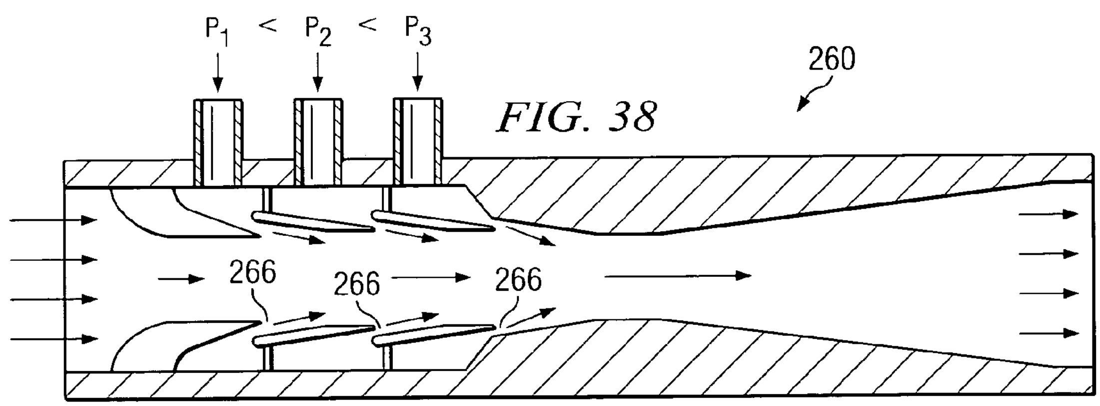


FIG. 38

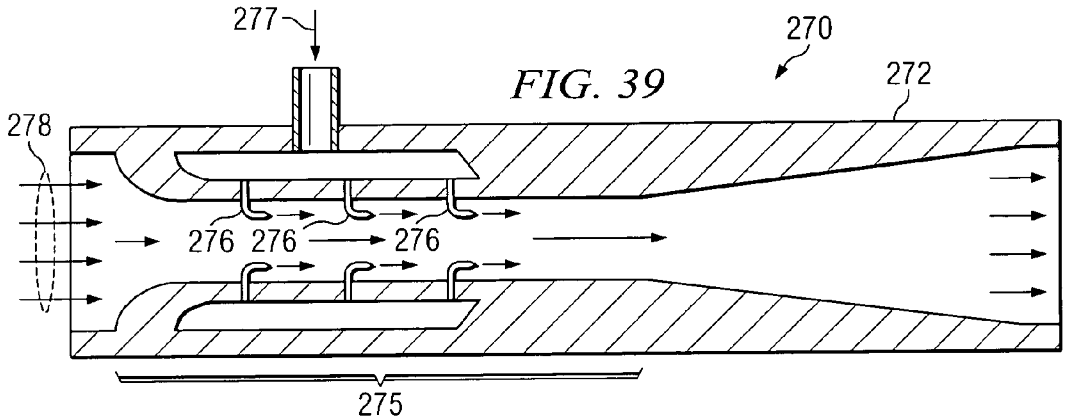


FIG. 39

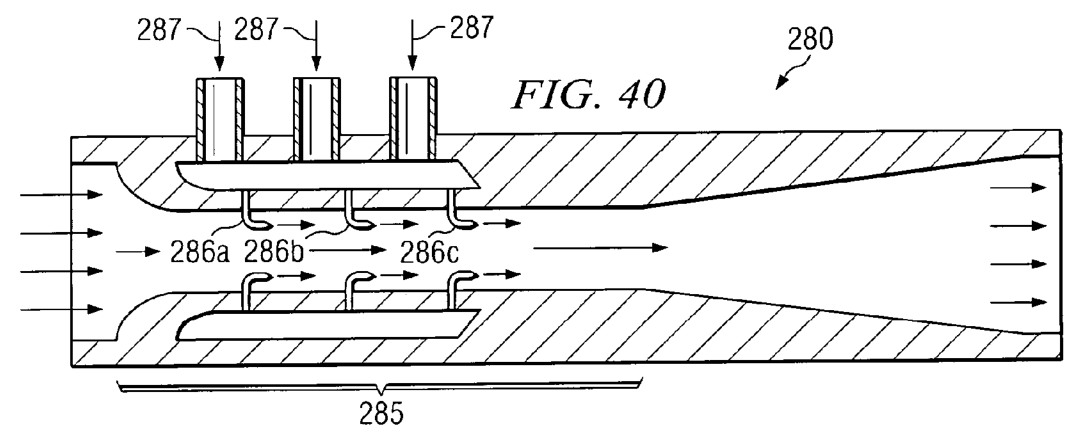


FIG. 40

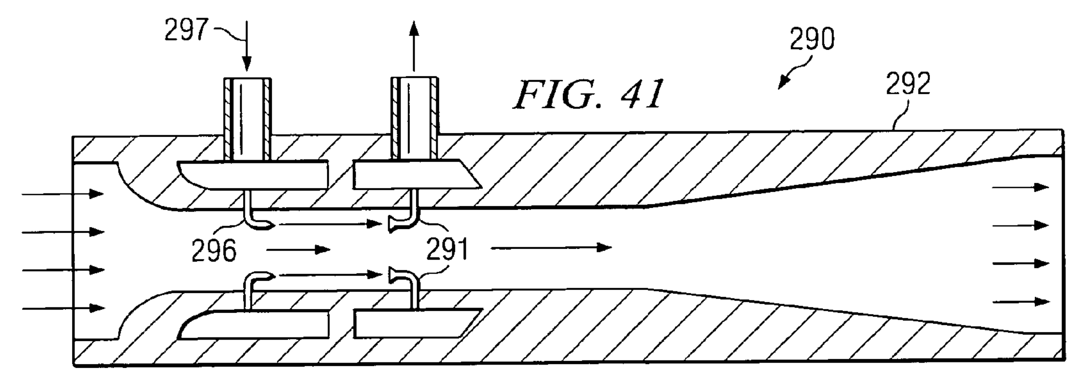
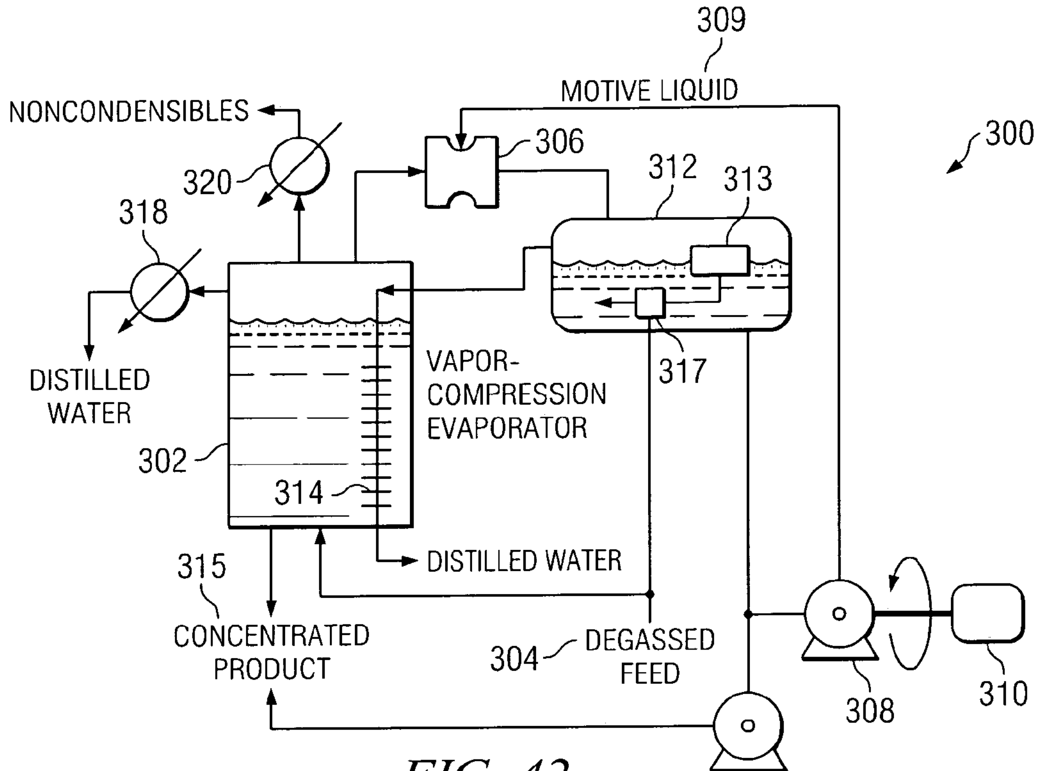
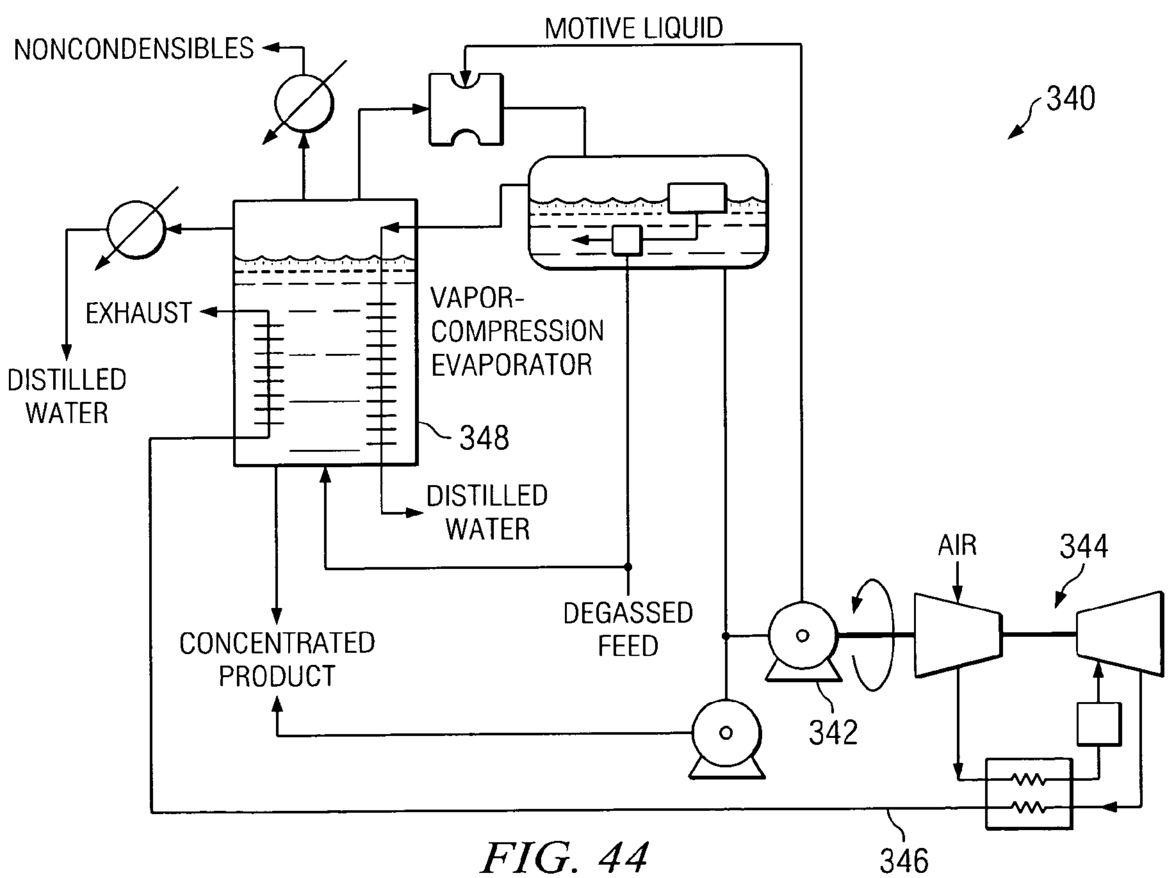


FIG. 41



309
MOTIVE LIQUID
NONCONDENSIBLES
306
300
320
312
313
318
VAPOR-
COMPRESSION
EVAPORATOR
DISTILLED
WATER
317
302
314
315
DISTILLED WATER
CONCENTRATED
PRODUCT
304
DEGASSED
FEED
308
310

FIG. 42



NONCONDENSIBLES
MOTIVE LIQUID
340
VAPOR-
COMPRESSION
EVAPORATOR
EXHAUST
DISTILLED
WATER
348
DISTILLED
WATER
AIR
344
DEGASSED
FEED
CONCENTRATED
PRODUCT
342
346

FIG. 44

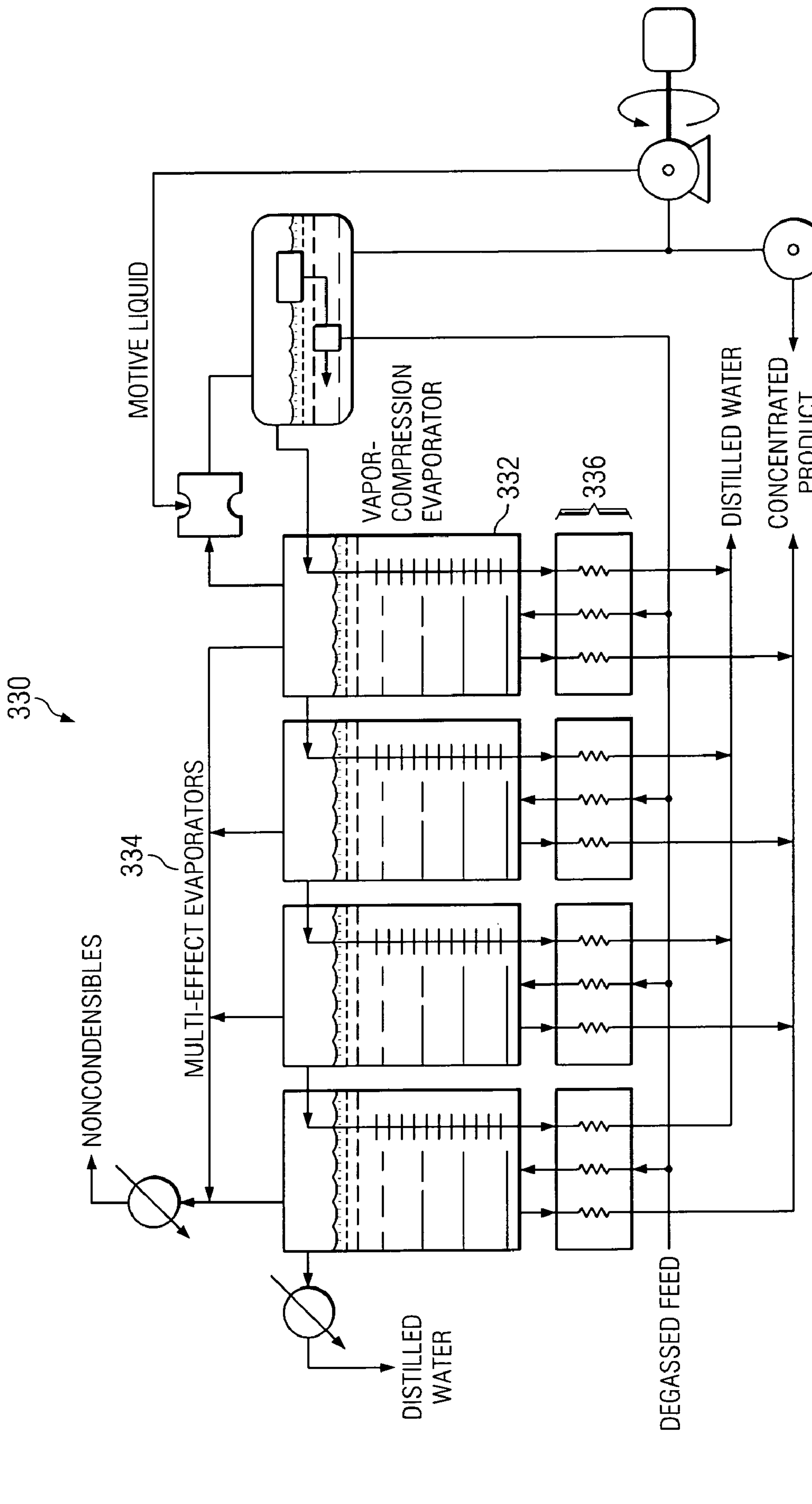

330
MOTIVE LIQUID
VAPOR-
COMPRESSION
EVAPORATOR
332
336
DISTILLED WATER
CONCENTRATED
PRODUCT
334
MULTI-EFFECT EVAPORATORS
NONCONDENSIBLES
DISTILLED
WATER
DEGASSED FEED

FIG. 43

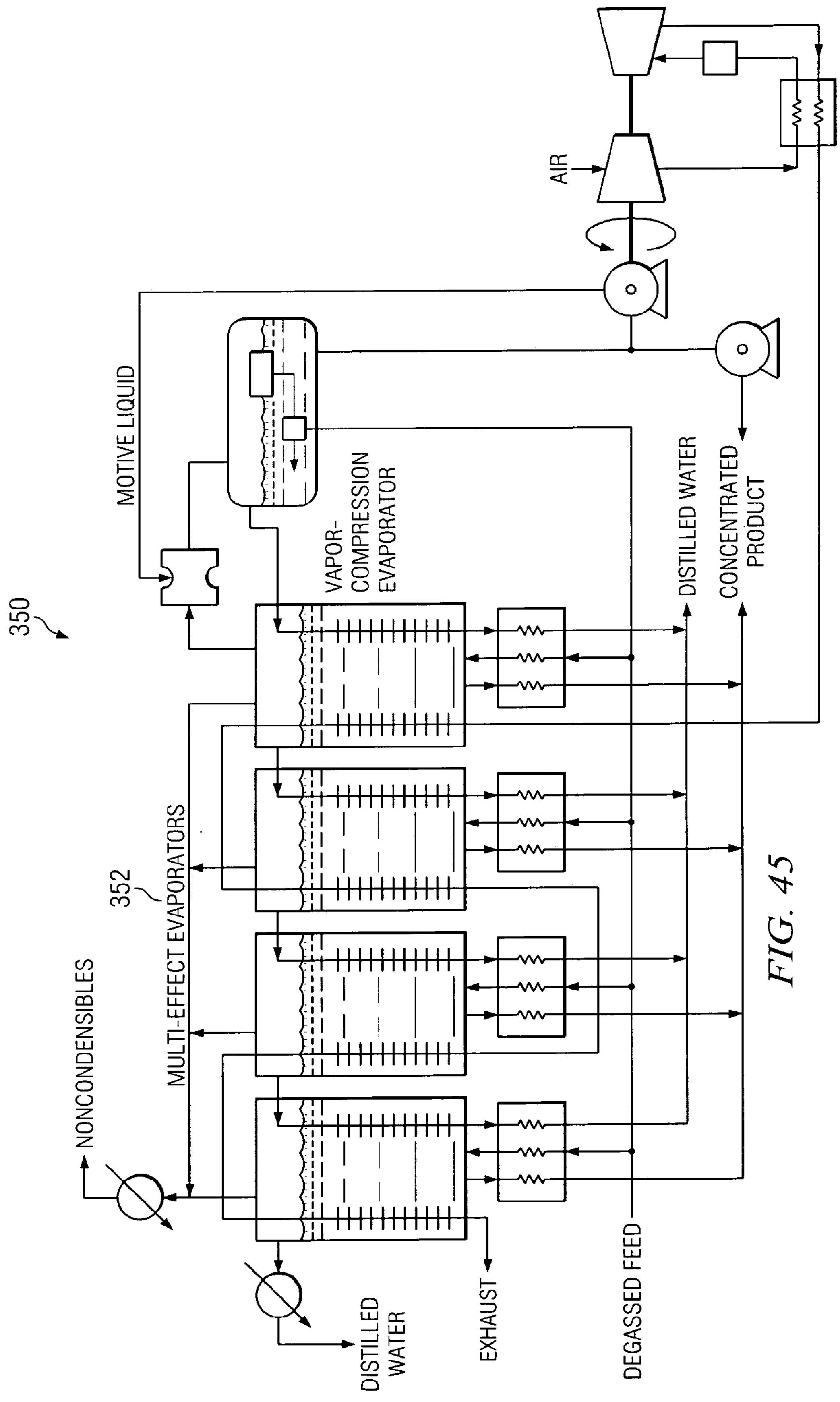

350
352
MULTI-EFFECT EVAPORATORS
NONCONDENSIBLES
MOTIVE LIQUID
VAPOR-
COMPRESSION
EVAPORATOR
AIR
DISTILLED WATER
CONCENTRATED
PRODUCT
DISTILLED
WATER
EXHAUST
DEGASSED FEED

FIG. 45

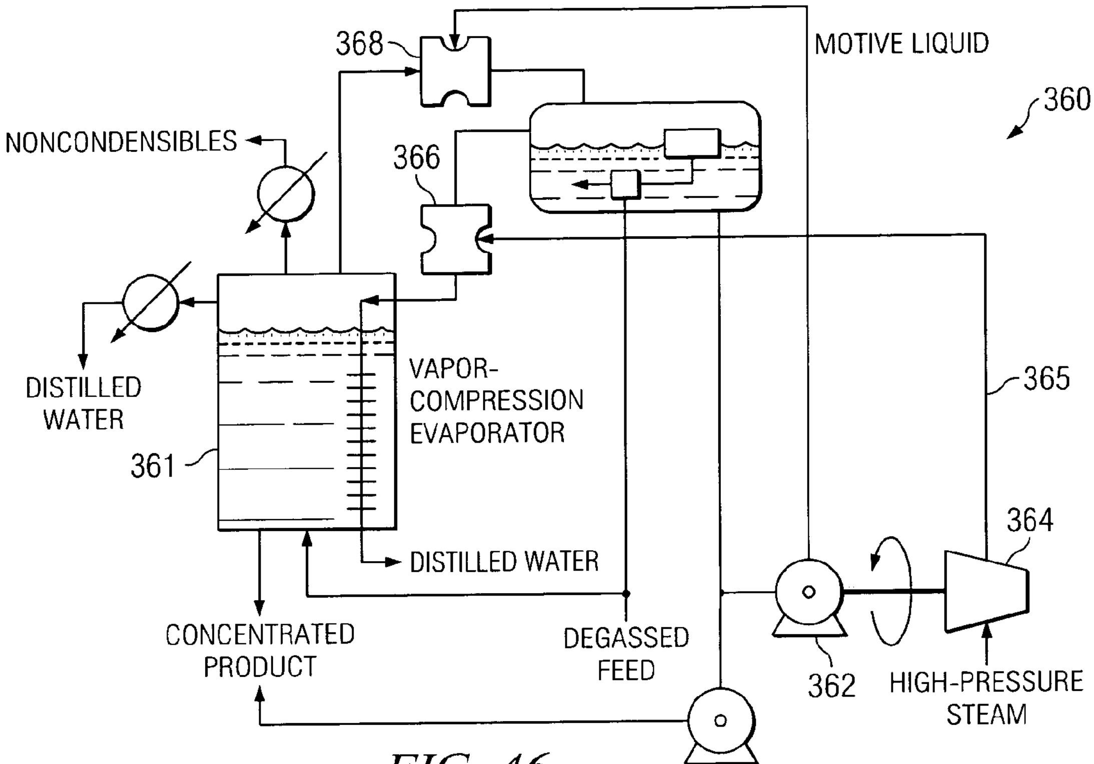

368
MOTIVE LIQUID
360
NONCONDENSIBLES
366
DISTILLED
WATER
VAPOR-
COMPRESSION
EVAPORATOR
365
361
364
DISTILLED WATER
CONCENTRATED
PRODUCT
DEGASSED
FEED
362
HIGH-PRESSURE
STEAM

FIG. 46

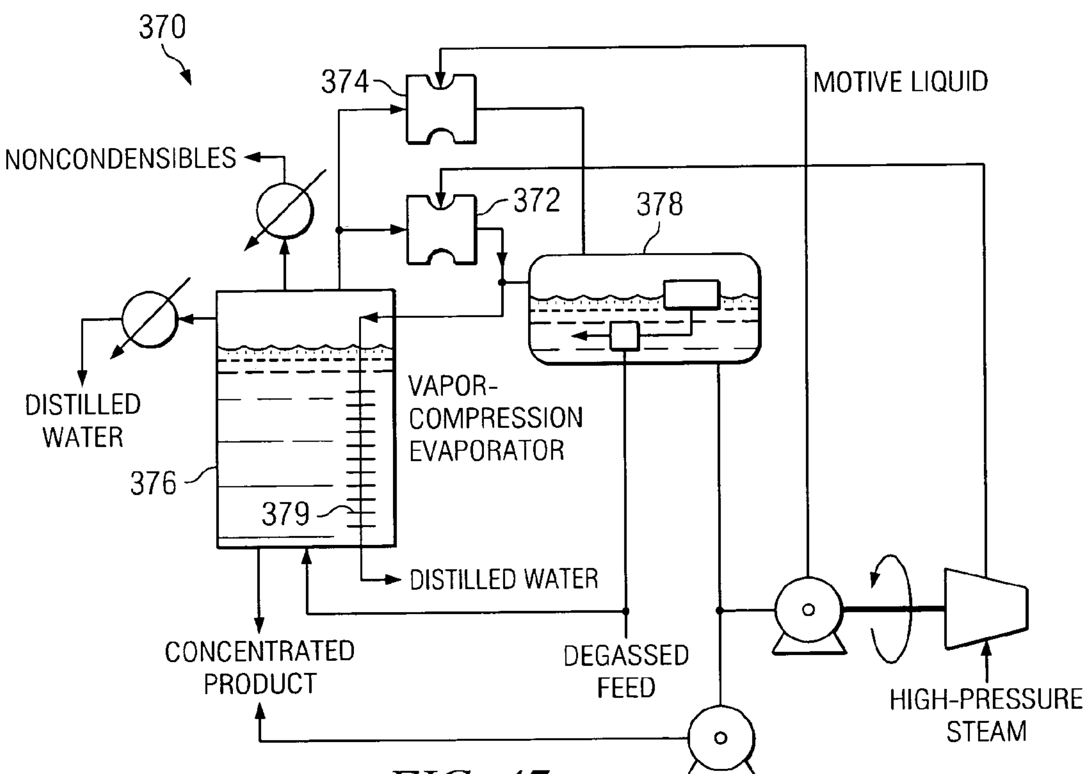
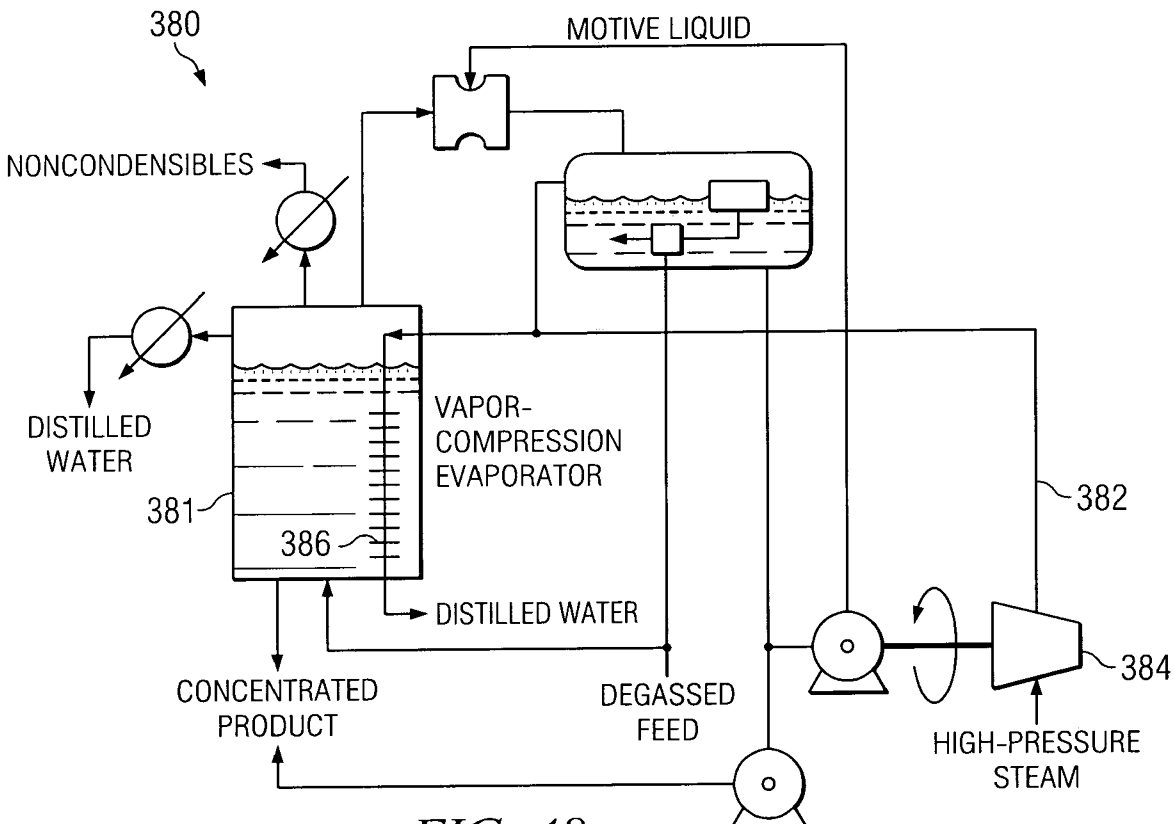

370
374
MOTIVE LIQUID
NONCONDENSIBLES
372
378
DISTILLED
WATER
VAPOR-
COMPRESSION
EVAPORATOR
376
379
DISTILLED WATER
CONCENTRATED
PRODUCT
DEGASSED
FEED
HIGH-PRESSURE
STEAM

FIG. 47



380
MOTIVE LIQUID
NONCONDENSIBLES
DISTILLED WATER
VAPOR-COMPRESSION EVAPORATOR
381
386
382
DISTILLED WATER
384
CONCENTRATED PRODUCT
DEGASSED FEED
HIGH-PRESSURE STEAM

FIG. 48

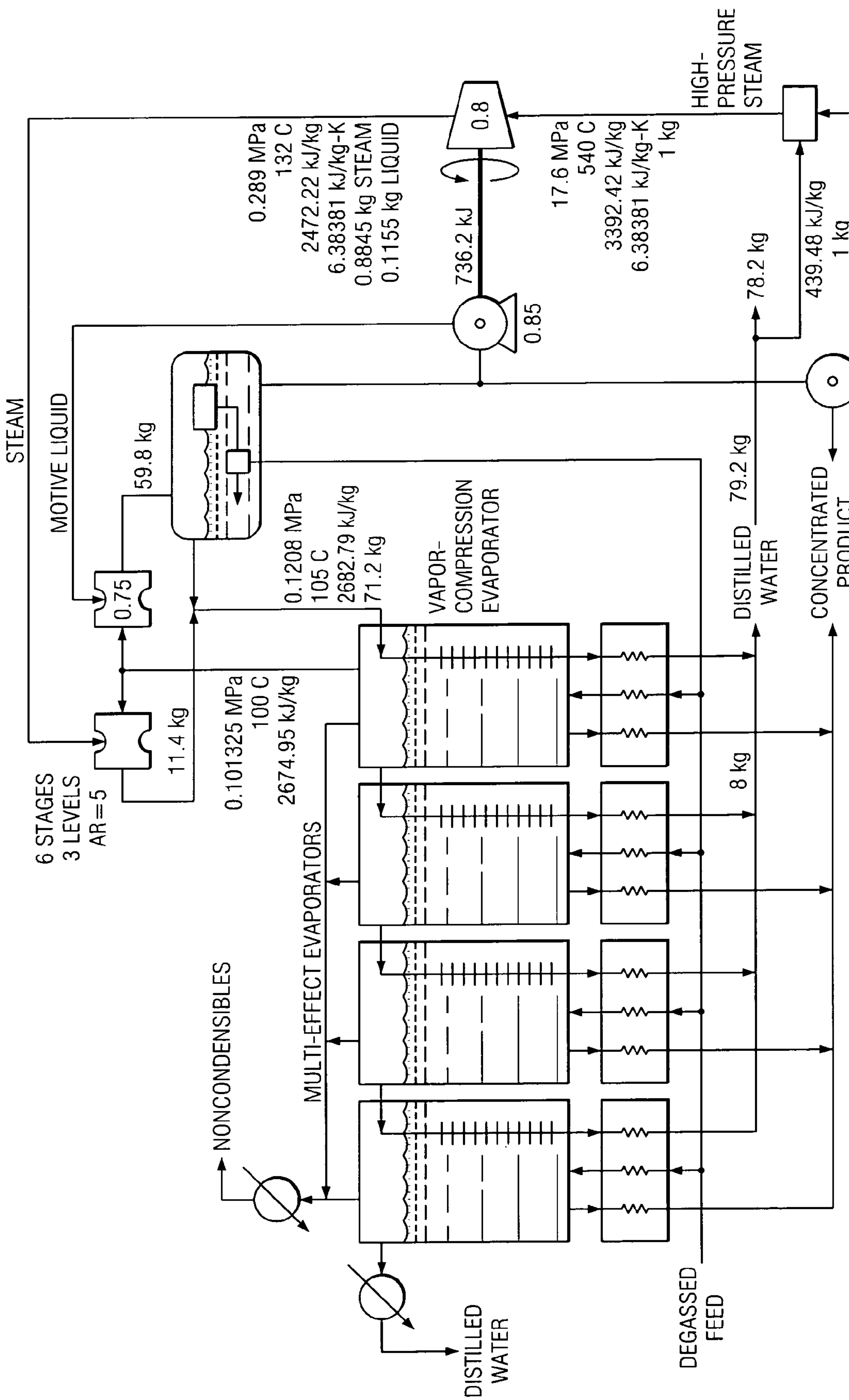
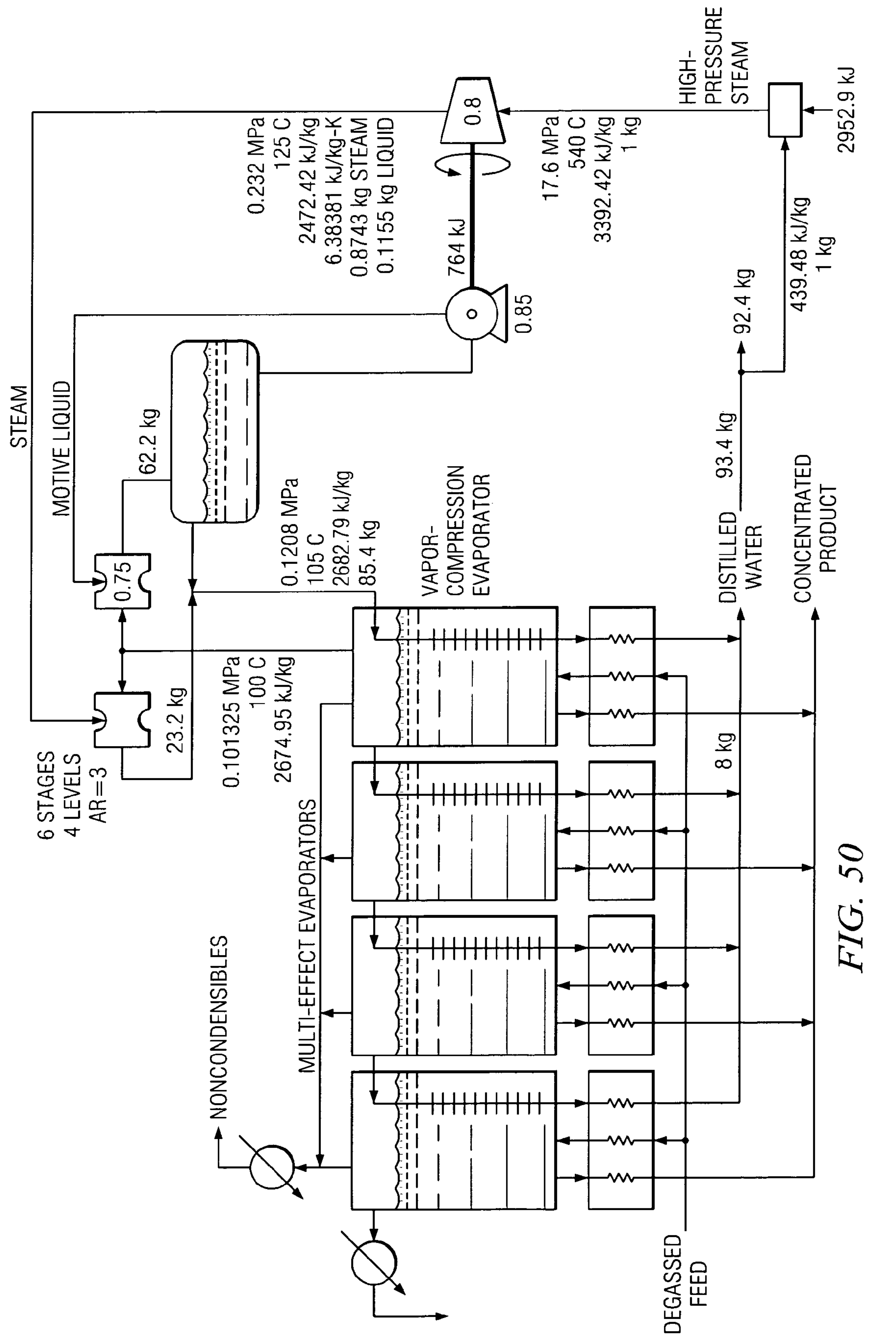

STEAM
MOTIVE LIQUID
59.8 kg
0.75
6 STAGES
3 LEVELS
AR=5
11.4 kg
0.101325 MPa
100 C
2674.95 kJ/kg
0.1208 MPa
105 C
2682.79 kJ/kg
71.2 kg
VAPOR-
COMPRESSION
EVAPORATOR
0.289 MPa
132 C
2472.22 kJ/kg
6.38381 kJ/kg-K
0.8845 kg STEAM
0.1155 kg LIQUID
0.8
736.2 kJ
0.85
17.6 MPa
540 C
3392.42 kJ/kg
6.38381 kJ/kg-K
1 kg
HIGH-
PRESSURE
STEAM
2952.9 kJ
78.2 kg
439.48 kJ/kg
1 kg
79.2 kg
DISTILLED
WATER
CONCENTRATED
PRODUCT
8 kg
MULTI-EFFECT EVAPORATORS
NONCONDENSIBLES
DISTILLED
WATER
DEGASSED
FEED

FIG. 49



HIGH-PRESSURE STEAM
2952.9 kJ
0.8
0.232 MPa
125 C
2472.42 kJ/kg
6.38381 kJ/kg-K
0.8743 kg STEAM
0.1155 kg LIQUID
17.6 MPa
540 C
3392.42 kJ/kg
1 kg
764 kJ
0.85
439.48 kJ/kg
1 kg
92.4 kg
93.4 kg
STEAM
MOTIVE LIQUID
62.2 kg
0.1208 MPa
105 C
2682.79 kJ/kg
85.4 kg
VAPOR-COMPRESSION EVAPORATOR
0.75
DISTILLED WATER
CONCENTRATED PRODUCT
0.101325 MPa
100 C
2674.95 kJ/kg
23.2 kg
6 STAGES
4 LEVELS
AR=3
8 kg
MULTI-EFFECT EVAPORATORS
NONCONDENSIBLES
DEGASSED FEED

FIG. 50

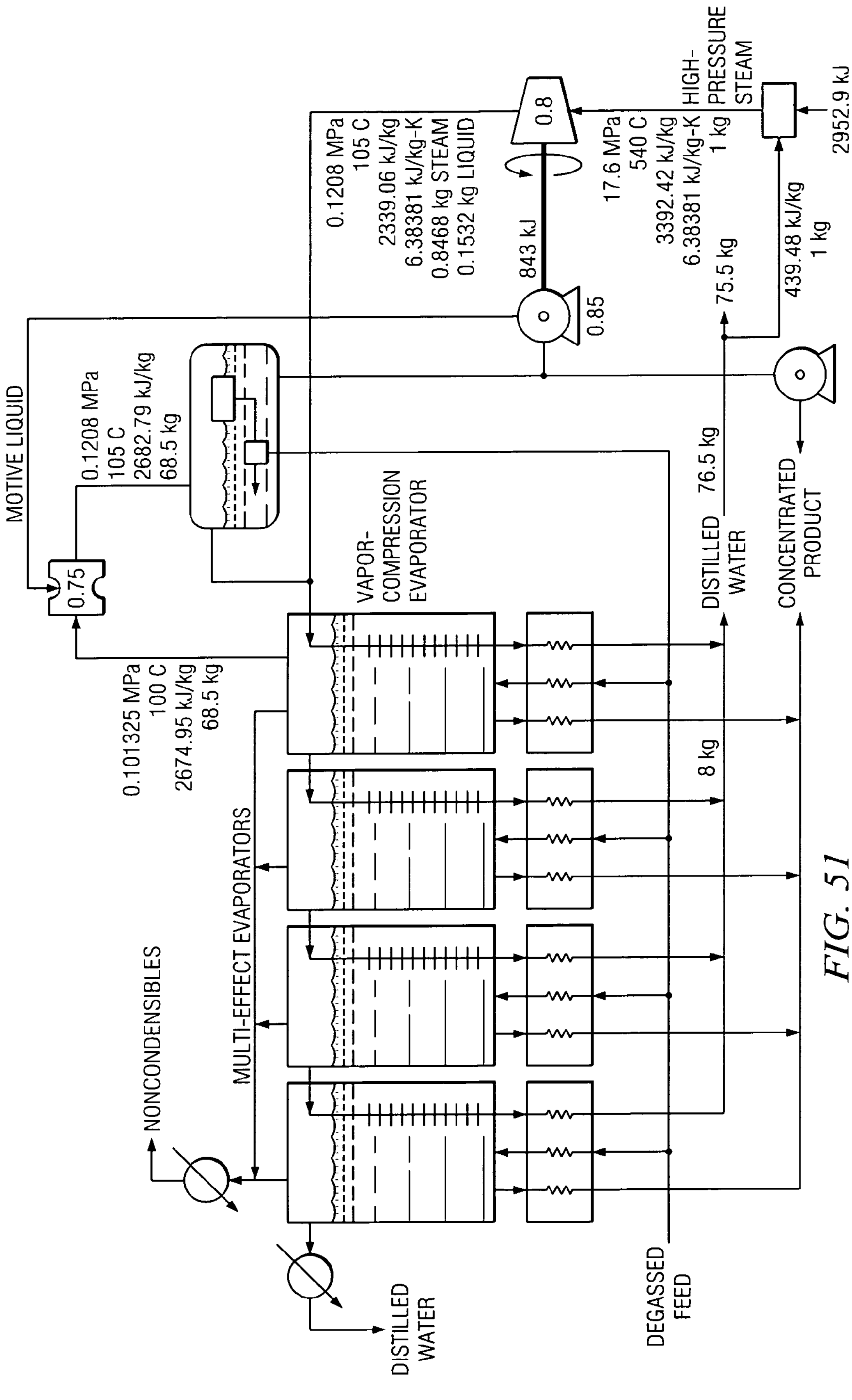
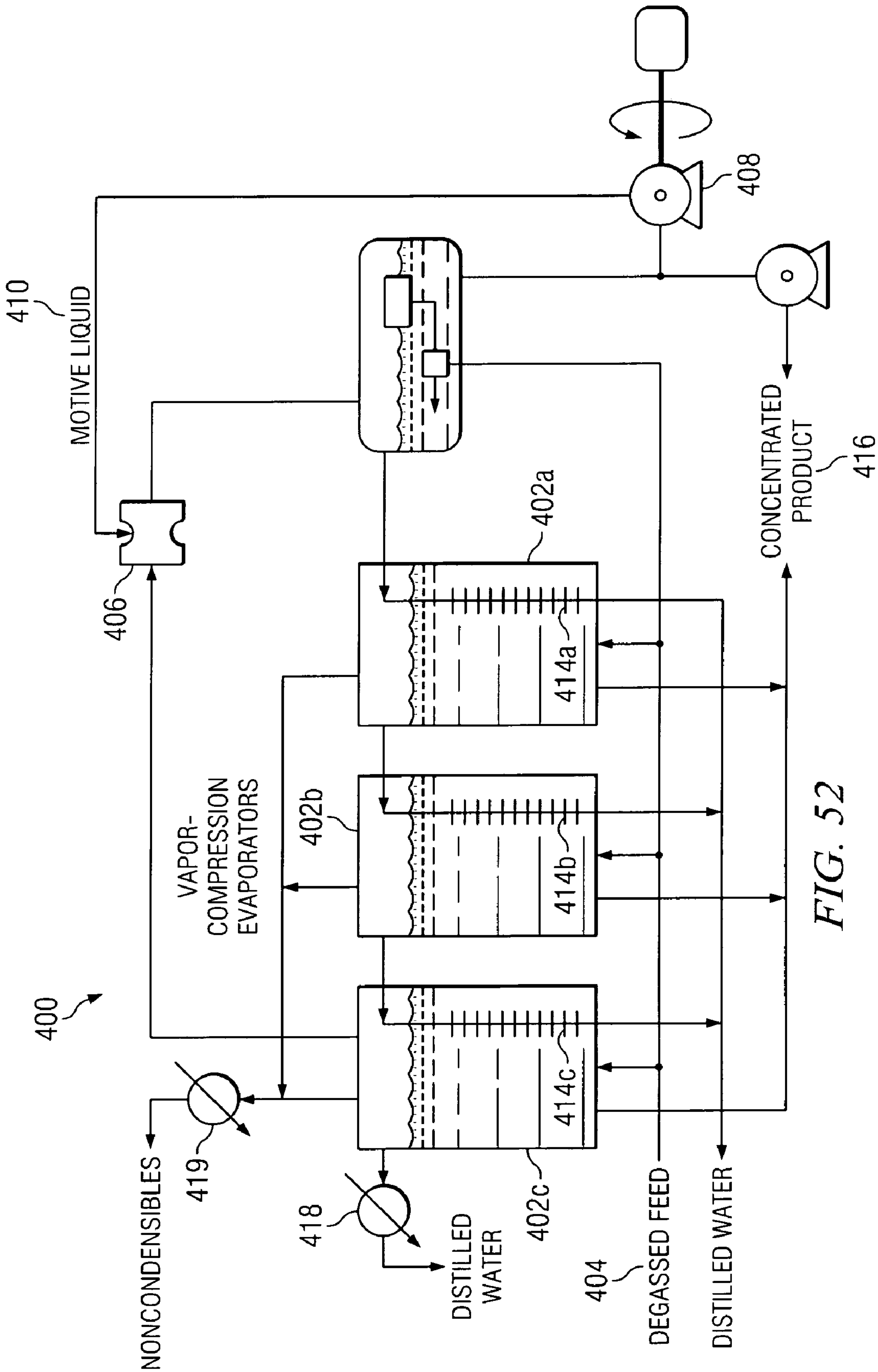

HIGH-PRESSURE STEAM
2952.9 kJ
0.8
0.1208 MPa
105 C
2339.06 kJ/kg
6.38381 kJ/kg-K
0.8468 kg STEAM
0.1532 kg LIQUID
17.6 MPa
540 C
3392.42 kJ/kg
6.38381 kJ/kg-K
1 kg
843 kJ
0.85
439.48 kJ/kg
1 kg
75.5 kg
MOTIVE LIQUID
0.1208 MPa
105 C
2682.79 kJ/kg
68.5 kg
0.75
VAPOR-COMPRESSION EVAPORATOR
DISTILLED WATER
76.5 kg
CONCENTRATED PRODUCT
0.101325 MPa
100 C
2674.95 kJ/kg
68.5 kg
8 kg
MULTI-EFFECT EVAPORATORS
NONCONDENSIBLES
DISTILLED WATER
DEGASSED FEED

FIG. 51



400
410
MOTIVE LIQUID
408
406
402a
414a
402b
414b
VAPOR-COMPRESSION EVAPORATORS
402c
414c
419
NONCONDENSIBLES
418
DISTILLED WATER
404
DEGASSED FEED
DISTILLED WATER
CONCENTRATED PRODUCT
416

FIG. 52

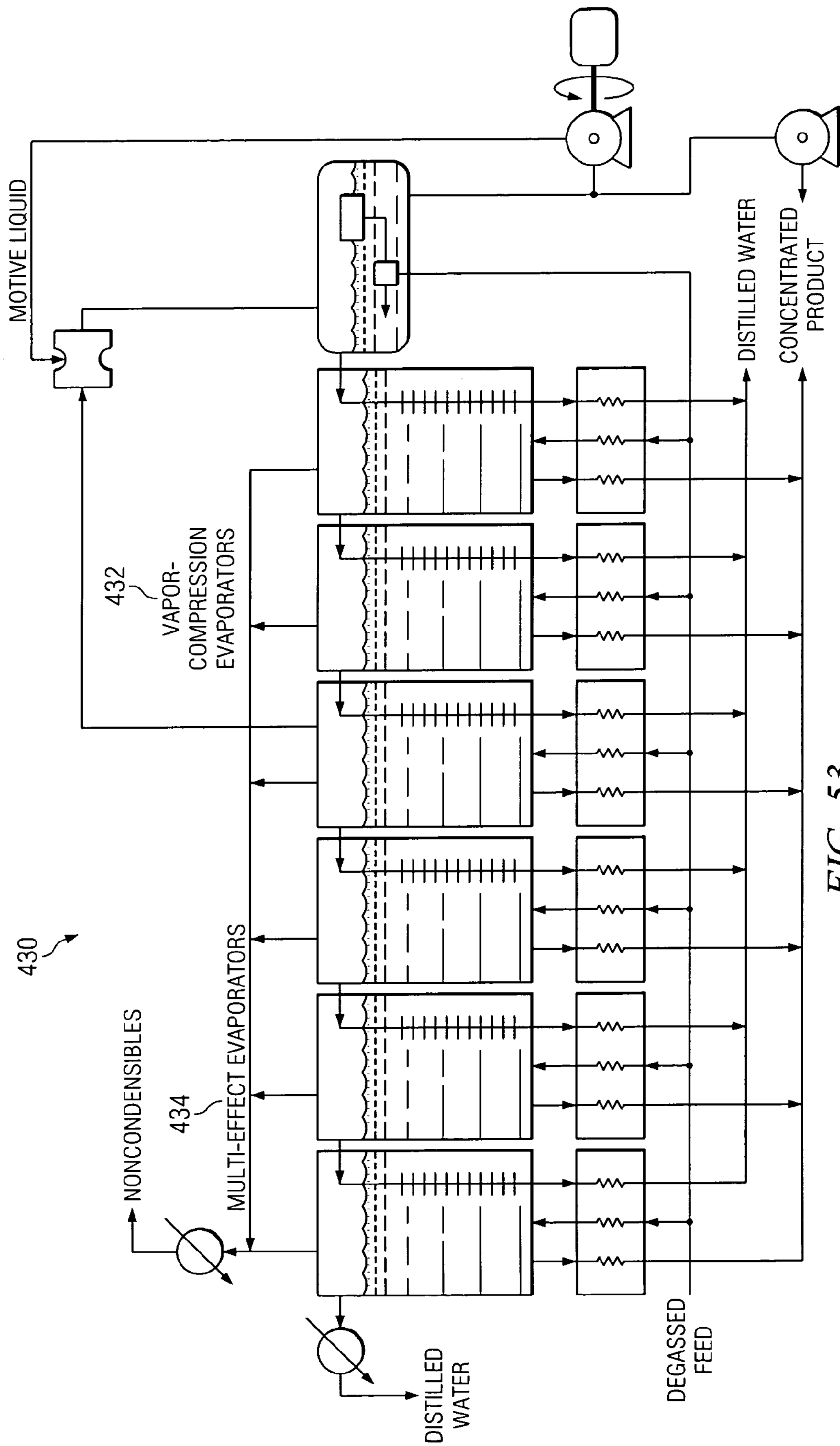

MOTIVE LIQUID
DISTILLED WATER
CONCENTRATED PRODUCT
432
VAPOR-COMPRESSION EVAPORATORS
430
NONCONDENSIBLES
434
MULTI-EFFECT EVAPORATORS
DISTILLED WATER
DEGASSED FEED

FIG. 53

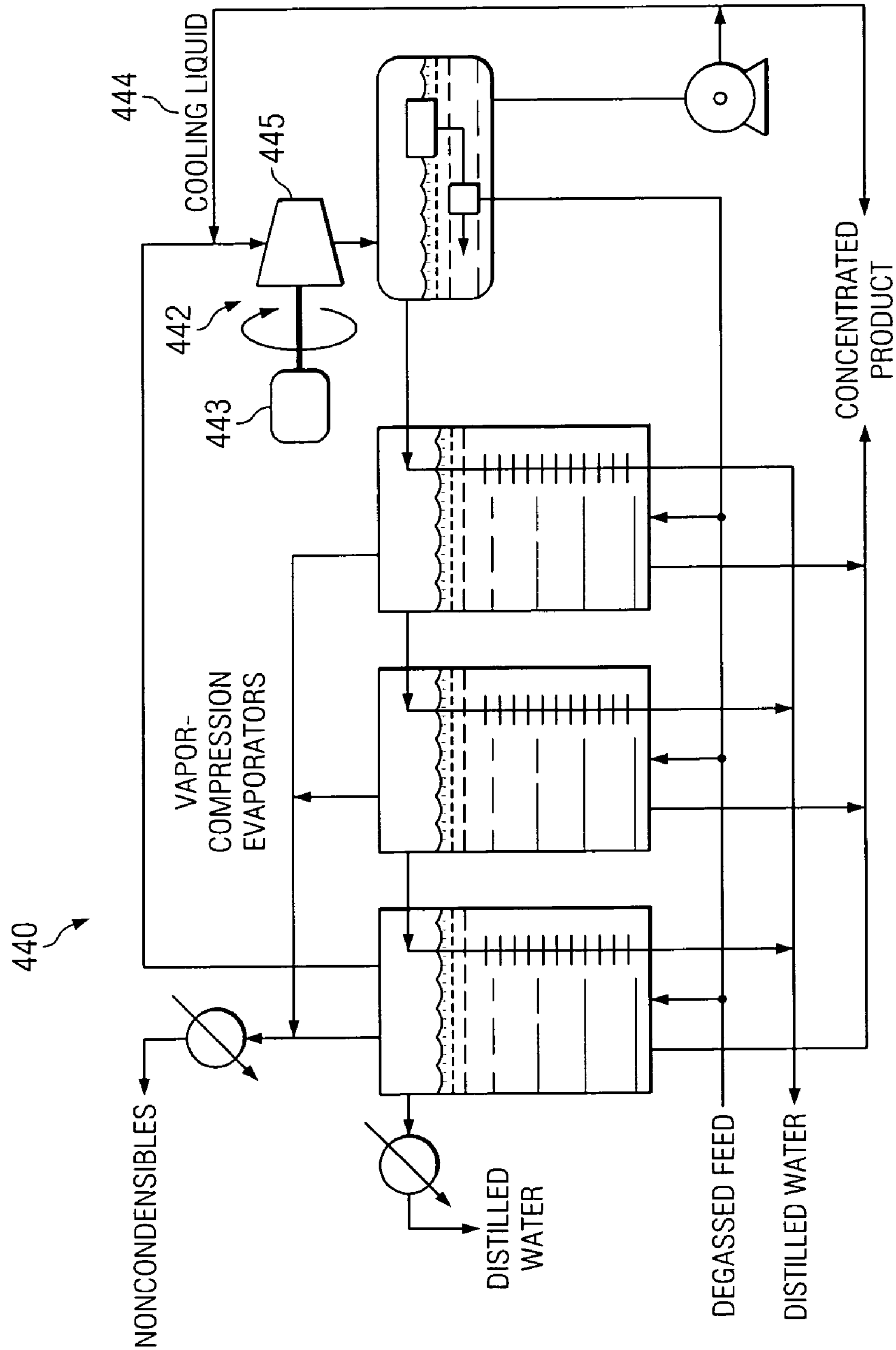

440
444
COOLING LIQUID
445
442
443
VAPOR-
COMPRESSION
EVAPORATORS
CONCENTRATED
PRODUCT
NONCONDENSIBLES
DISTILLED
WATER
DEGASSED FEED
DISTILLED WATER

FIG. 54

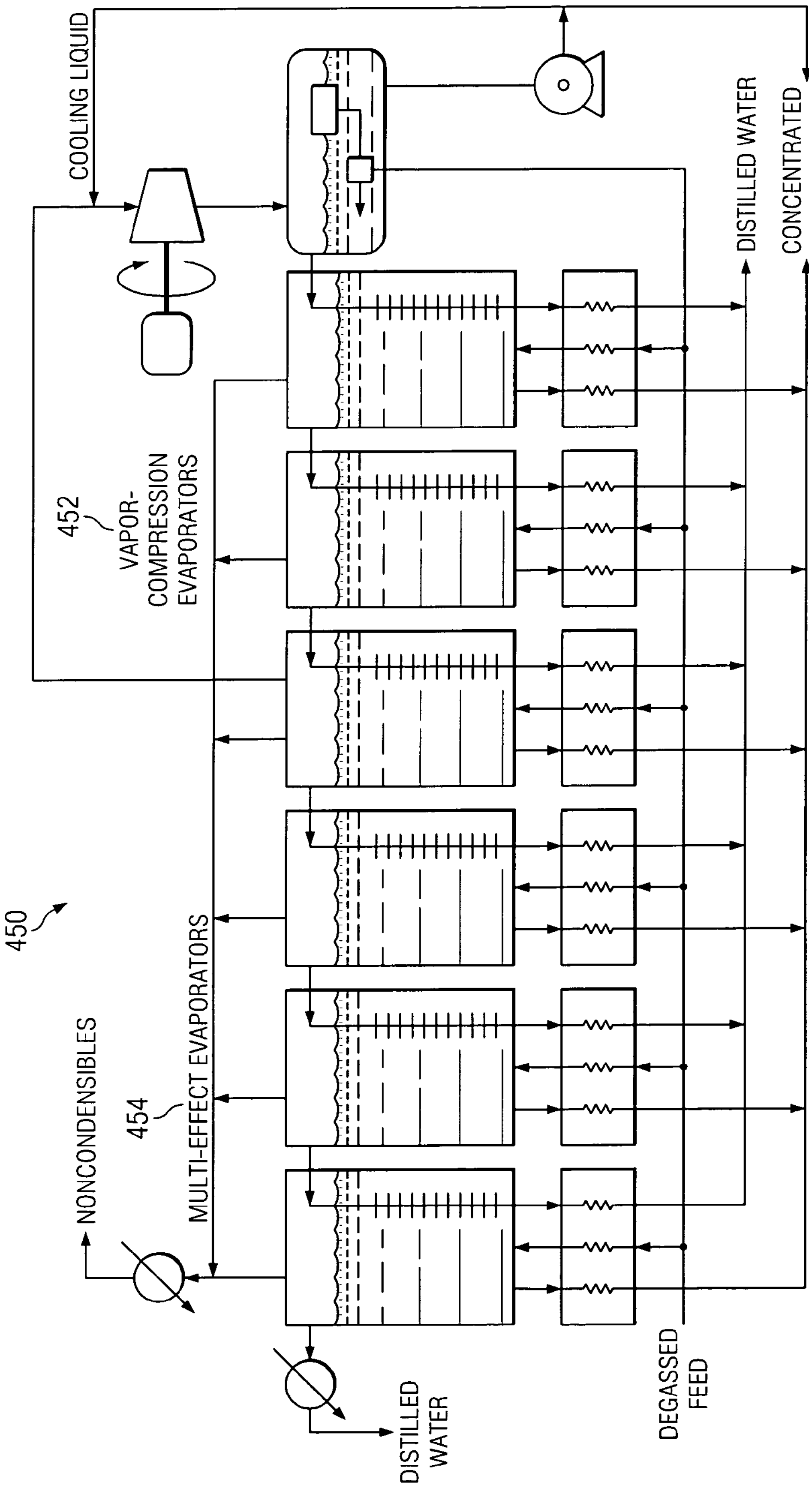

COOLING LIQUID
DISTILLED WATER
CONCENTRATED PRODUCT
452
VAPOR-COMPRESSION EVAPORATORS
450
NONCONDENSIBLES
454
MULTI-EFFECT EVAPORATORS
DISTILLED WATER
DEGASSED FEED

FIG. 55

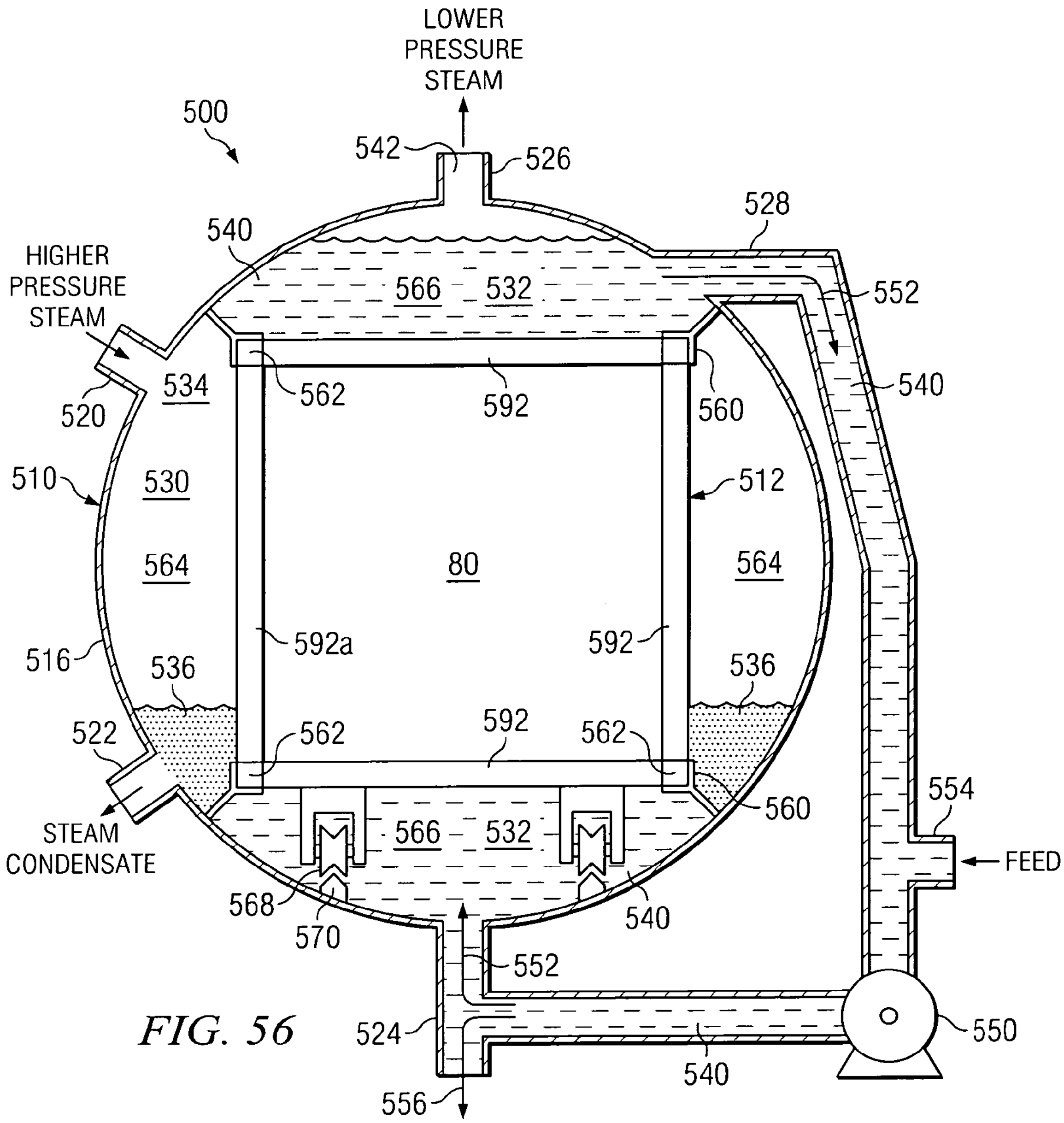

LOWER
PRESSURE
STEAM
500
542
526
528
540
566
532
552
HIGHER
PRESSURE
STEAM
534
562
592
560
540
520
510
530
512
564
80
564
516
592a
592
536
536
522
562
592
562
560
STEAM
CONDENSATE
566
532
554
FEED
568
570
540
552
524
550
540
556

FIG. 56

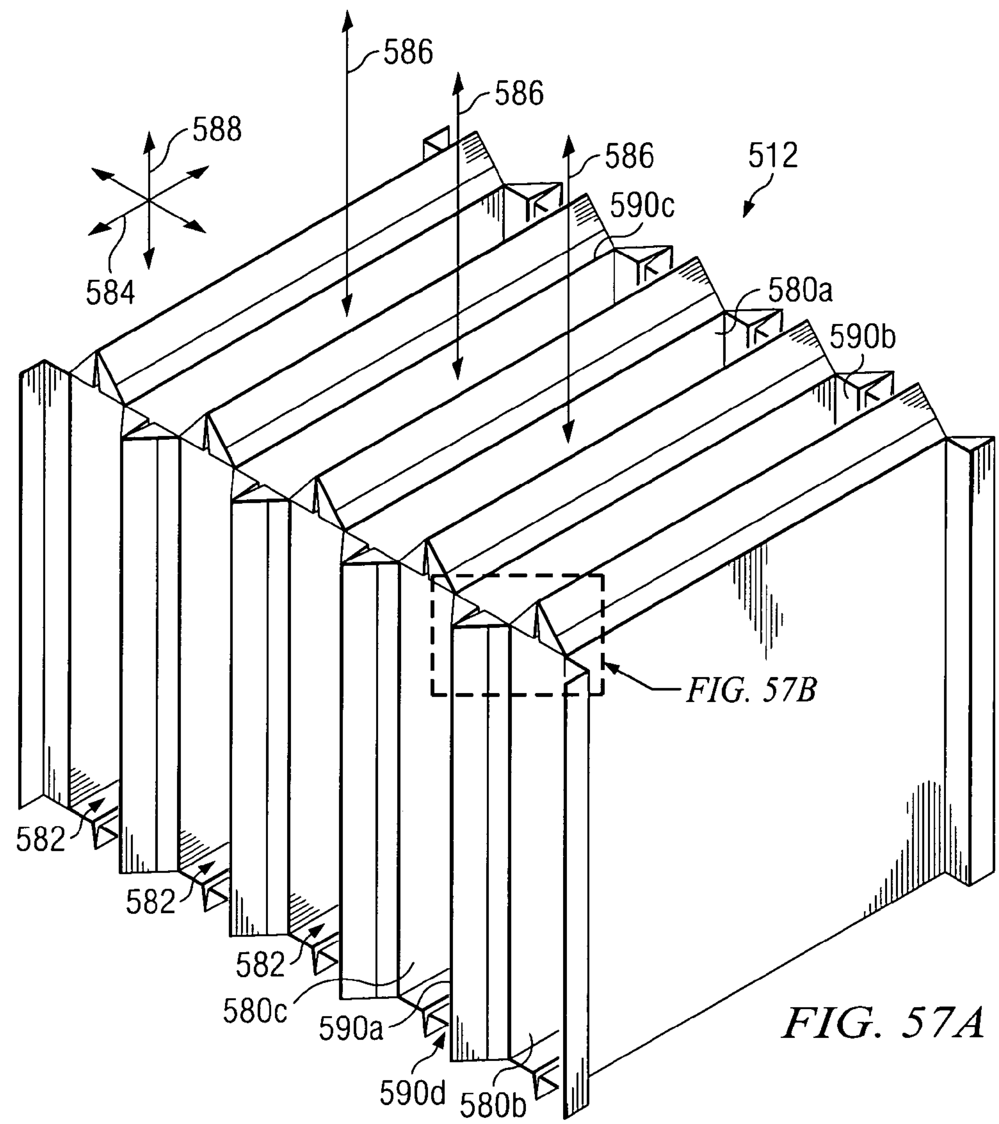


FIG. 57A

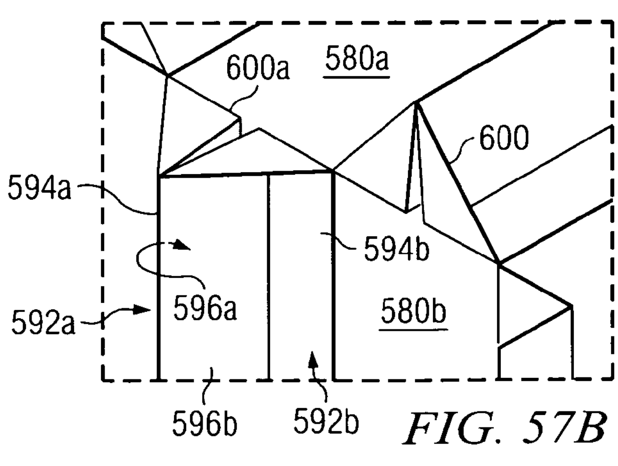


FIG. 57B

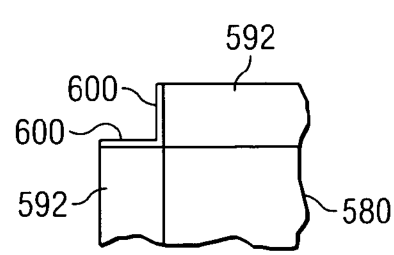


FIG. 57C

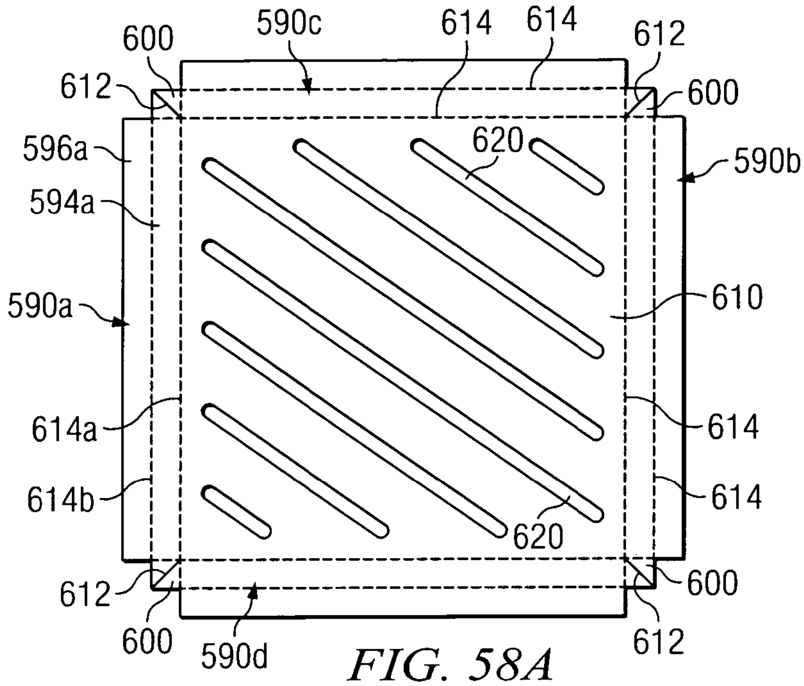


FIG. 58A

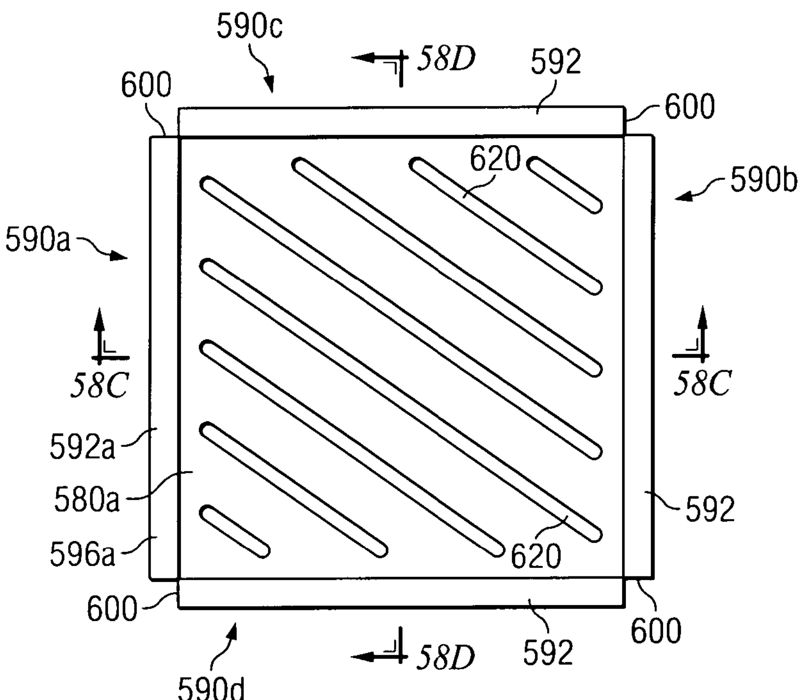


FIG. 58B

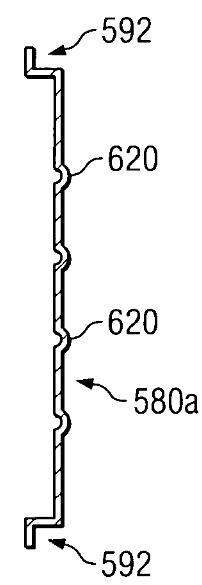


FIG. 58D

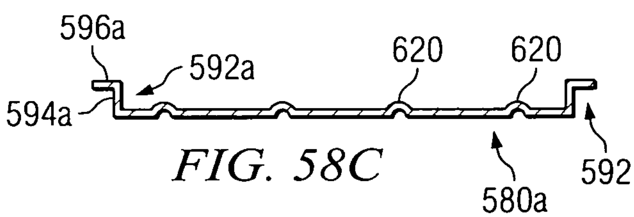


FIG. 58C

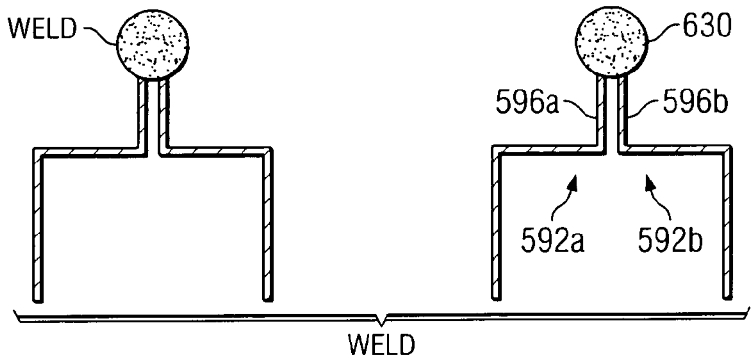


FIG. 59A

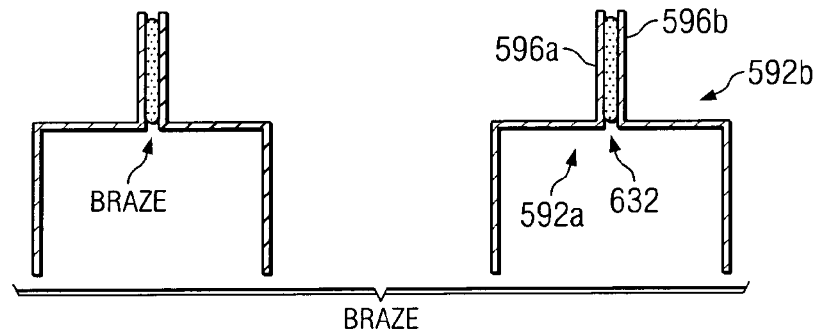


FIG. 59B

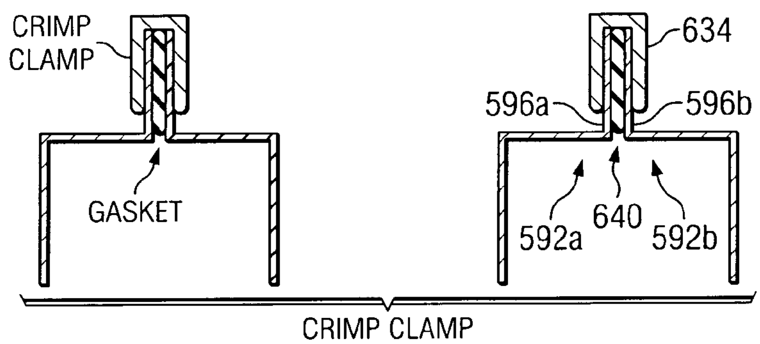


FIG. 59C

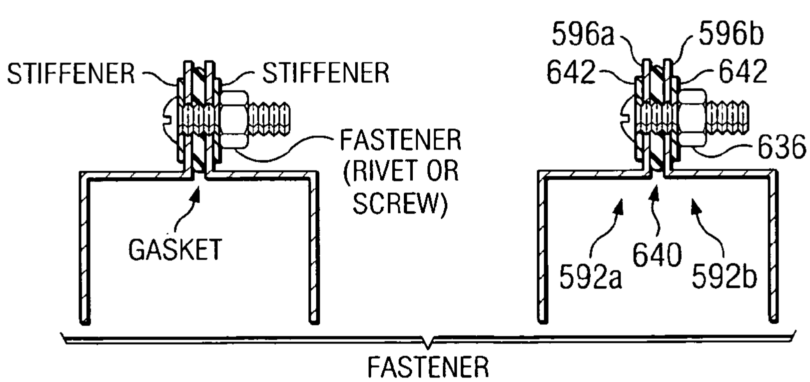


FIG. 59D

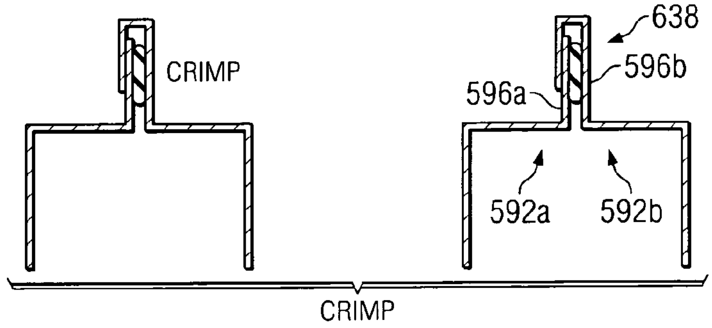


FIG. 59E

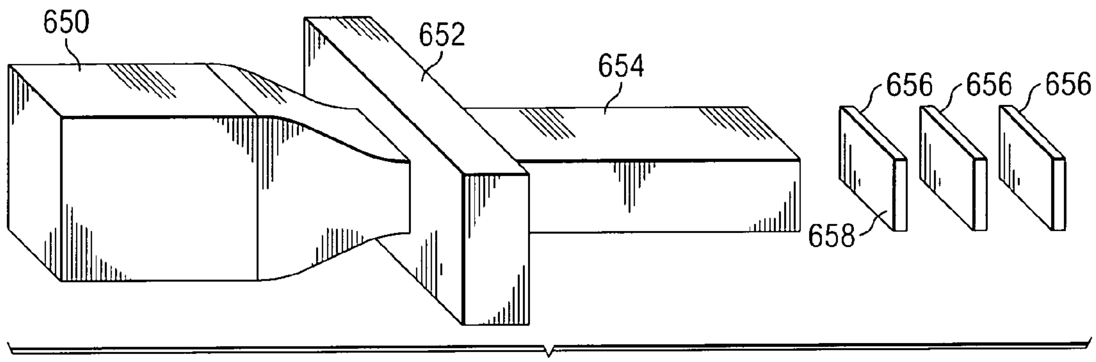


FIG. 60A

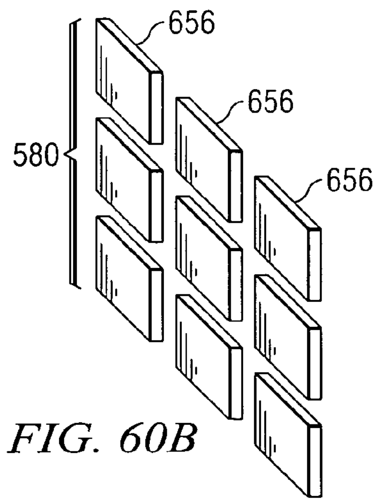


FIG. 60B

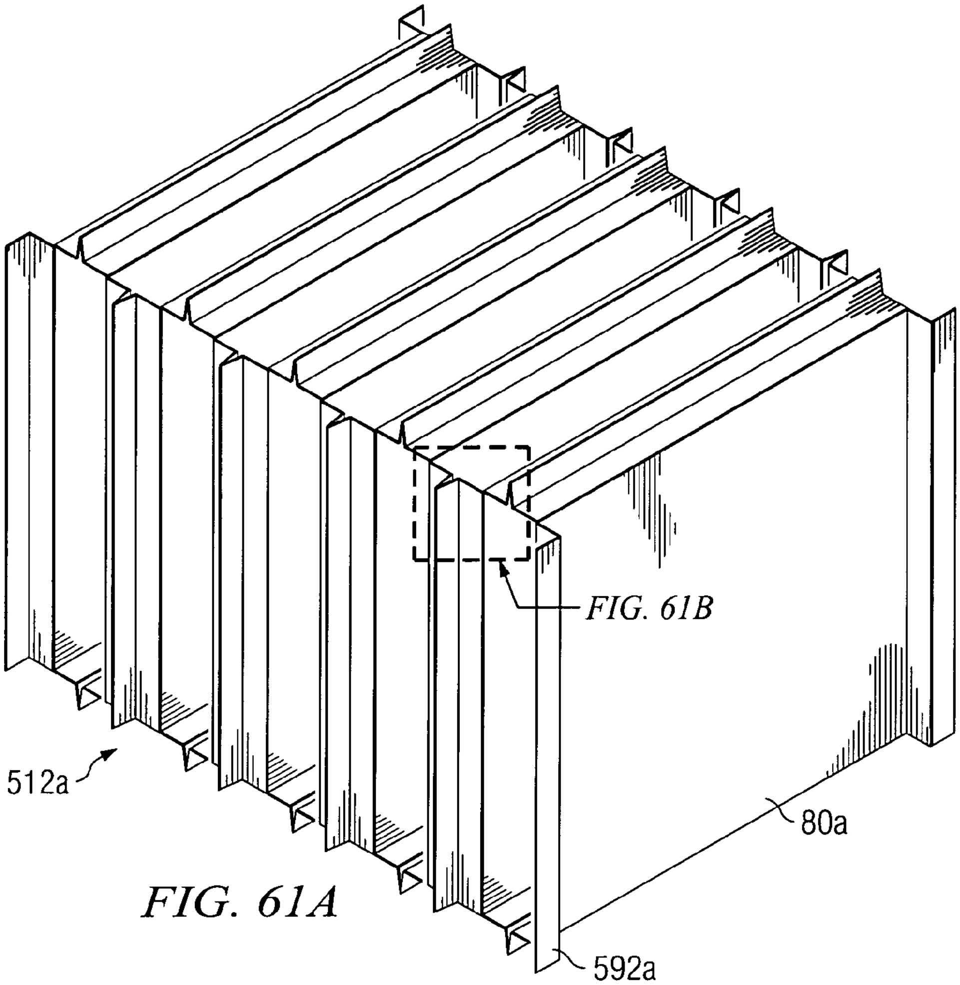


FIG. 61A

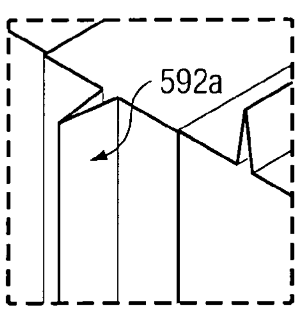


FIG. 61B

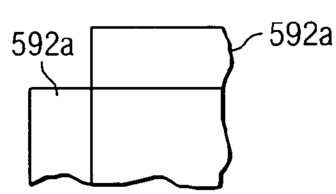


FIG. 61C

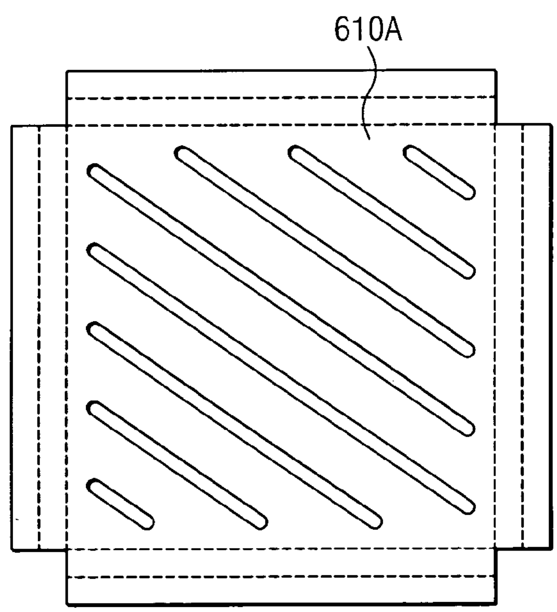


FIG. 61D

JET EJECTOR SYSTEM AND METHOD

RELATED APPLICATIONS

This application claims the benefit of Ser. No. 60/504,138 titled "Jet Ejector System and Method," filed provisionally on Sep. 19, 2003.

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to the field of jet ejectors and, more particularly, to an improved, ultra-high efficiency jet ejector system and method.

BACKGROUND OF THE INVENTION

Typical steam jet ejectors feed high-pressure steam, at relatively high velocity, into the jet ejector. Steam is usually used as the motive fluid because it is readily available; however, an ejector may be designed to work with other gases or vapors as well. For some applications, water and other liquids are sometimes good motive fluids as they condense large quantities of vapor instead of having to compress them. Liquid motive fluids may also compress gases or vapors.

The motive high-pressure steam enters a nozzle and issues into the suction head as a high-velocity, low-pressure jet. The nozzle is an efficient device for converting the enthalpy of high-pressure steam or other fluid into kinetic energy. A suction head connects to the system being evacuated. The high-velocity jet issues from the nozzle and rushes through the suction head.

Gases or vapors from the system being evacuated enter the suction head where they are entrained by the high-velocity motive fluid, which accelerates them to a high velocity and sweeps them into the diffuser. The process in the diffuser is the reverse of that in the nozzle. It transforms a high-velocity, low-pressure jet stream into a high-pressure, low-velocity stream. Thus, in the final stage, the high-velocity stream passes through the diffuser and is exhausted at the pressure of the discharge line.

SUMMARY OF THE INVENTION

According to one embodiment of the invention, a jet ejector method includes providing a primary jet ejector having a primary inlet stream, coupling one or more secondary jet ejectors to the primary jet ejector such that all of the jet ejectors are in a cascaded arrangement, bleeding off a portion of the primary inlet stream and directing the portion of the primary inlet stream to the secondary jet ejector that is closest to the primary jet ejector in the cascaded arrangement, and directing a motive fluid into the secondary jet ejector that is farthest from the primary jet ejector in the cascaded arrangement. The method further includes, at each secondary jet ejector, receiving at least some of the portion of the primary inlet stream and at least some of the motive fluid to create respective mixtures within the secondary jet ejectors, and at each secondary jet ejector, directing at least a portion of the respective mixture to adjacent jet ejectors in the cascaded arrangement.

According to another embodiment of the invention, a jet ejector includes a nozzle having a first stream flowing therethrough and including an upstream portion, a downstream portion, and a throat disposed between the upstream portion and the downstream portion, a plurality of sets of apertures located in a wall of the nozzle in the throat, wherein the plurality of sets are longitudinally spaced along the wall and each set of apertures having its apertures circumferentially located around the wall, and a device operable to inject a motive fluid through the apertures and into the first stream.

Embodiments of the invention provide a number of technical advantages. Embodiments of the invention may include all, some, or none of these advantages. An advantage of a jet ejector system according to one embodiment of the invention is that it blends gas streams of similar pressures; therefore, the velocity of each gas stream is similar. This leads to high efficiencies, even using traditional jet ejectors. The efficiency may be improved further by improving the design of the jet ejector.

A jet ejector according to one embodiment of the invention blends gas streams of similar velocities, but does not obstruct the flow of the propelled gas. This jet ejector may be used in many applications, such as compressors, heat pumps, water-based air conditioning, vacuum pumps, and propulsive jets (both for watercraft and aircraft).

An advantage of another jet ejector system according to one embodiment of the invention is it uses a high-efficiency liquid jet ejector in a cost-effective dewatering system. When combined with steam jet ejectors and multi-effect evaporators, any energy inefficiencies of the liquid jet system (liquid jet itself, pump, turbine) produce heat that usefully distills liquid. This liquid jet ejector may be used in water-based air conditioning.

In other embodiments, a heat exchanger is designed to facilitate a lower pressure drop than existing heat exchangers at low cost. Such a heat exchanger may include a plurality of plates (or sheets) inside a tube. The plates may be made of any suitable material; however, for some embodiments in which corrosion is a concern, the plates may be made of a suitable polymer.

Other technical advantages are readily apparent to one skilled in the art from the following figures, descriptions, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the invention, and for further features and advantages, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

FIG. **1** illustrates a low-pressure vapor-compression evaporator system;

FIG. **2** illustrates a medium-pressure vapor-compression evaporator system;

FIG. **3** is a graphical correlation for standard jet ejectors;

FIG. **4** illustrates P_{motive}/P_{inlet} (the inverse of the y-axis in FIG. **3**) as a function of compression ratio (P_{outlet}/P_{inlet}) for each area ratio, AR;

FIG. **5** illustrates the slopes of FIG. **4** on a log-log graph;

FIG. **6** illustrates m_{motive}/m_{inlet} (the inverse of the x-axis in FIG. **3**) as a function of compression ratio (P_{outlet}/P_{inlet}) for each area ratio, AR;

FIG. **7** illustrates the slopes of FIG. **6** on a log-log graph;

FIG. **8** illustrates a jet ejector system according to one embodiment of the invention;

FIGS. **9** through **20** illustrate the pressures and mass flows (using arbitrary units) according to various embodiments of the invention;

FIGS. **21** through **31** illustrate various jet ejector systems according to various embodiments of the invention;

FIG. **32** illustrates a jet ejector according to one embodiment of the invention;

FIG. **33** illustrates a jet ejector according to another embodiment of the invention;

FIGS. **34** and **35** illustrate a jet ejector according to another embodiment of the invention;

FIG. **36** illustrates a pattern of nozzle ducts according to one embodiment of the invention;

FIG. **37** illustrates a liquid jet ejector according to one embodiment of the invention;

FIG. **38** illustrates a liquid jet ejector according to another embodiment of the invention;

FIG. **39** illustrates a liquid jet ejector according to another embodiment of the invention;

FIG. **40** illustrates a liquid jet ejector according to another embodiment of the invention;

FIG. **41** illustrates a liquid jet ejector according to another embodiment of the invention;

FIGS. **42** through **51** illustrate various embodiments of an evaporator system that incorporates a liquid jet ejector according to various embodiments of the invention;

FIGS. **52** through **55** illustrate various embodiments of a vapor-compression evaporator system according to various embodiments of the invention;

FIG. **56** illustrates a cross-section of an example heat exchanger assembly including a shell and a sheet assembly disposed within the shell in accordance with an embodiment of the invention;

FIG. **57**A illustrates a three-dimensional view of the sheet assembly of the heat exchanger assembly of FIG. **56** in accordance with one embodiment of the invention;

FIG. **57**B is a blown-up view of a corner area of the sheet assembly of FIG. **57**A in accordance with an embodiment of the invention;

FIG. **57**C illustrates a side view of the corner of sheet assembly illustrated in FIG. **57**B;

FIGS. **58**A-**58**B illustrate an example method of forming a particular sheet of the sheet assembly shown in FIG. **57**A in accordance with one embodiment of the invention;

FIG. **59** illustrates various example manners for coupling the flange portions of adjacent sheets of the sheet assembly shown in FIG. **57**A in accordance with one embodiment of the invention;

FIG. **60**A illustrates a method of aligning the molecules in a polymer for making polymer sheets in accordance with one embodiment of the invention;

FIG. **60**B illustrates a method of forming a sheet for a sheet assembly by joining a number of polymer sheets in accordance with one embodiment of the invention; and

FIGS. **61**A-**61**D illustrates another example sheet assembly in accordance with another embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** illustrates a low-pressure vapor-compression evaporator system **2** performing desalination of salt water. A salt-containing feed **3** flows into an evaporator tank **4**, which in this embodiment is operated under vacuum. Although, in the illustrated embodiment, feed **3** is a salt-containing feed, a sugar-containing feed or suitable feed is also contemplated by the present invention. The salt-containing feed **3** boils, producing low-pressure vapors. These vapors are removed from evaporator tank **4** using a jet ejector **5**. The pressurized vapors exiting jet ejector **5** flow into a heat exchanger **6**, where they condense. Because of the interaction of heat exchanger **6** and evaporator tank **4**, the heat of condensation provides the heat of evaporation needed by the salt-containing feed **3**. Distilled liquid water **7** is recovered from heat exchanger **6** in any suitable manner, and concentrated salt solution **8** is removed from evaporator tank **4** using any suitable devices. The motive steam **9** added to jet ejector **5** may be condensed against cooling water; however, this condensation step may be eliminated if the product water is removed at a higher temperature than the feed water. A small vapor stream may be removed from evaporator tank **4** and sent to a condenser **10** to remove water vapor. The remaining gas is primarily noncondensibles, which may be removed using a vacuum pump (not explicitly illustrated).

FIG. **2** illustrates a medium-pressure vapor-compression evaporator system **20** according to an embodiment of the invention. System **20** operates similarly to system **2** in FIG. **1**, except that an evaporator tank **22** operates at a moderate pressure, for example one atm. A motive steam **23** is added to a jet ejector **24** and exits evaporator tank **22** at moderate pressure and is useful for evaporating water. In the embodiment illustrated in FIG. **2**, this medium-pressure steam may be used in a multi-effect evaporator **26**, although a multi-stage flash evaporator may be used as well.

In the illustrated embodiment, multi-effect evaporator **26** includes any suitable number of tanks **27***a*, **27***b*, **27***c* in series each containing a feed **28** having a nonvolatile component, such as salt or sugar. Jet ejector **24** coupled to evaporator tank **22** and receives a vapor from evaporator tank **22**. A heat exchanger **29** in evaporator tank **22** receives the vapor from jet ejector **24** where at least some of the vapor condenses therein. The heat of condensation provides the heat of evaporation to evaporator tank **22**. At least some of the vapor inside evaporator tank **22** is delivered to a heat exchanger **30***a* in tank **27***a*, whereby the condensing, evaporating, and delivering steps continue through each tank until the last tank in the series (in this embodiment, tank **27***c*) is reached.

System **20** may also include a condenser **32** coupled to tank **27***c* for removing energy from system **20**, and a vacuum pump (not illustrated) for removing noncondensibles from system **20**. Any suitable devices may be utilized for removing concentrated feed **33** from tanks **22** and **27***a*-**27***c*, and a plurality of sensible heat exchangers **34** may be coupled to tanks **22** and **27***a*-**27***c* for heating the feed **28** before entering the tanks **22**, **27***a*-**27***c*. Sensible heat exchangers **34** may also be utilized for other suitable functions.

The pressure difference between the condensing steam and the boiling feed **28** depends upon the temperature difference between heat exchanger **29** and evaporator tank **22**. In addition, salts (or other soluble materials) depress the vapor pressure, which increases the pressure difference even further. Table 1 illustrates the required compression ratio for pure water (i.e., no salt) as a function of the temperature difference.

TABLE 1

Required compression ratio for water as a function of temperature difference across the heat exchanger

Temperature Difference (° C.)	Compression Ratio $T_{evaporator}$ = 100° C.	Compression Ratio $T_{evaporator}$ = 25° C.
1	1.0362	1.0612
2	1.0735	1.1256
3	1.1119	1.1934
4	1.1514	1.2647
5	1.1921	1.3397
6	1.2340	1.4185
7	1.2770	1.5013
8	1.3210	1.5883

The required temperature difference depends upon the cost of heat exchangers and the cost of capital. In one embodiment, a temperature difference of 5° C. is considered economical. For a medium-pressure vapor-compression evaporator, such as system **20**, the required compression ratio is approximately 1.2.

FIG. **3** illustrates a correlation for conventional jet ejectors. Table 2 illustrates the properties of a conventional jet ejector, based upon FIG. **3**. Table 2 illustrates that using an area ratio of 100, 15.38-atm (226-psi) steam is able to evaporate 6.3 kg of water per kg of steam. Using system **20** (FIG. **2**) as an example, the steam exits the evaporator tank **22** at 1 atm and can evaporate more water in multi-effect evaporators **26** or a multi-stage flash evaporator. In industry, multi-stage flash evaporators typically evaporate 8 kg of water per kg of steam, so the entire medium-pressure vapor-compression system **20** can evaporate about 14 kg of distilled water per kg of steam. If the efficiency of jet ejector **24** can be improved, then the yield of distilled water may improve further.

TABLE 2

Required pressure and motive steam consumption for $\Delta T = 5°$ C. and $T_{evaporator} = 100°$ C.

Compression Ratio	Area Ratio	$\frac{P_{inlet}}{P_{motive}}$	P_{motive} (atm)	$\frac{m_{inlet}}{m_{motive}}$
1.2	100	0.065	15.38	6.3
1.2	50	0.115	8.70	5.7
1.2	25	0.200	5.00	4.5

For optimization purposes, it is desirable to find equations that present the same information. FIG. **4** illustrates P_{motive}/P_{inlet} (the inverse of the y-axis in FIG. **3**) as a function of compression ratio (P_{outlet}/P_{inlet}) for each area ratio, AR. As illustrated, each line is straight in FIG. **4**. FIG. **5** illustrates the slopes versus area ratio on a log-log graph. From FIGS. **4** and **5**, the following equation relates the parameters:

$$\frac{P_{motive}}{P_{inlet}} = 1 + 0.9848(AR)^{0.9072}\left(\frac{P_{outlet}}{P_{inlet}} - 1\right) \quad (1)$$

FIG. **6** illustrates m_{motive}/m_{inlet} (the inverse of the x-axis in FIG. **3**) as a function of compression ratio (P_{outlet}/P_{inlet}) for each area ratio, AR. Again, the lines are straight. FIG. **7** illustrates the slopes versus area ratio on a log-log graph. From FIGS. **6** and **7**, the following equation relates the parameters:

$$\frac{m_{motive}}{m_{inlet}} = 5.1179(AR)^{-0.4112}\left(\frac{P_{outlet}}{P_{inlet}} - 1\right) \quad (2)$$

One reason jet ejectors may be inefficient is because they blend two gas streams with widely different velocities, which may occur when the motive pressure is significantly different from the inlet pressure. Thus, according to the teachings of one embodiment of the invention, the efficiency of jet ejectors may be improved substantially by developing jet ejectors and/or jet ejector systems that accomplish the required compression task by minimizing P_{motive}/P_{inlet}.

FIGS. **8** through **31** illustrate various embodiments of an improved design of a ultrahigh-efficiency jet ejector system that allows motive gas and propelled gas to be blended in a manner that minimizes the velocity differences between the two streams, thus optimizing efficiency. Some embodiments may also allow for the energy to be added in the form of work, rather than heat, which increases efficiency even further.

FIG. **8** illustrates a jet ejector system **50**, according to one embodiment of the invention, that minimizes P_{motive}/P_{inlet}. In the illustrated embodiment, system **50** includes a primary jet ejector **52** and one or more secondary jet ejectors **56***a*, **56***b*, **56***c* coupled to primary jet ejector **52** such that all of the jet ejectors are in a cascaded arrangement. As illustrated by various embodiments below in conjunction with FIGS. **9**-**31**, this cascaded arrangement may be any suitable network of secondary jet ejectors **56** that receive a portion of a primary inlet stream **54** from primary jet ejector **52** and a motive steam **58** and process these streams before feeding a portion of the mixture of these streams back to primary jet ejector **52** for creation of primary outlet stream **55**. Primary jet ejector **52** is analogous to jet ejector **5** of FIG. **1** or jet ejector **24** of FIG. **2**.

In FIG. **8**, a portion of primary inlet stream **54** is bled off and directed to secondary jet ejector **56***a* and, as described above, motive steam **58** is directed into secondary jet ejector **56***c*. At each secondary jet ejector **56**, at least some of the portion of primary inlet stream **54** and at least some of motive steam **58** is received to create respective mixtures within secondary jet ejectors **56**. And at each secondary jet ejector **56** at least a portion of the respective mixture is directed to adjacent jet ejectors (**56** or **52**) in the cascaded arrangement.

For various embodiments of the invention utilizing the concept of FIG. **8**, Tables 3 through 6 show the required P_{motive}/P_{inlet} (Equation 1) and the resulting m_{motive}/m_{inlet} (Equation 2) for each secondary jet ejector (also referred to as a stage) in the cascade. FIGS. **9** through **20** illustrate the pressures and mass flows for each embodiment shown. Because any suitable operating parameters are contemplated by the present invention, the pressure units and mass units are arbitrarily shown in FIGS. **9** through **20**; however, it may be convenient to use atmospheres for pressure and kilograms for mass.

TABLE 3

Analysis of jet ejector for compression ratio of 1.03.

Area Ratio	Stage	$\frac{P_{outlet}}{P_{inlet}}$	$\frac{P_{motive}}{P_{inlet}}$	$\frac{m_{motive}}{m_{inlet}}$
5	1	1.03	1.127	0.079
	2	1.13	1.539	0.335
	3	1.37	2.552	0.966
	4	1.86	4.647	2.271
	5	2.49	7.319	3.934
4	1	1.03	1.104	0.087
	2	1.10	1.360	0.301
	3	1.23	1.804	0.671
	4	1.46	2.607	1.343
	5	1.78	3.704	2.260
	6	2.08	4.741	3.126
	7	2.28	5.427	3.699
3	1	1.03	1.080	0.098
	2	1.08	1.213	0.261
	3	1.12	1.331	0.404
	4	1.33	1.883	1.078
	5	1.41	2.105	1.349
	6	1.49	2.300	1.588
	7	1.55	2.457	1.779
	8	1.59	2.571	1.919
	9	1.62	2.649	2.013

TABLE 4

Analysis of jet ejector for compression ratio of 1.05.

Area Ratio	Stage	$\frac{P_{outlet}}{P_{inlet}}$	$\frac{P_{motive}}{P_{inlet}}$	$\frac{m_{motive}}{m_{inlet}}$
5	1	1.05	1.212	0.132
	2	1.21	1.899	0.560
	3	1.57	3.405	1.497
	4	2.17	5.975	3.097
	5	2.75	8.421	4.621
4	1	1.05	1.173	0.145
	2	1.17	1.599	0.501
	3	1.36	2.257	1.051
	4	1.66	3.269	1.896
	5	1.97	4.374	2.819
	6	2.21	5.205	3.514
3	1	1.05	1.133	0.163
	2	1.13	1.355	0.433
	3	1.20	1.523	0.638
	4	1.27	1.731	0.893
	5	1.36	1.958	1.169
	6	1.44	2.173	1.433
	7	1.51	2.358	1.658
	8	1.56	2.499	1.831
	9	1.6	2.601	1.955

TABLE 5

Analysis of jet ejector for compression ratio of 1.1.

Area Ratio	Stage	$\frac{P_{outlet}}{P_{inlet}}$	$\frac{P_{motive}}{P_{inlet}}$	$\frac{m_{motive}}{m_{inlet}}$
5	1	1.10	1.424	0.264
	2	1.42	2.798	1.120
	3	1.97	5.092	2.548
	4	2.59	7.751	4.204
4	1	1.10	1.346	0.289
	2	1.35	2.198	1.001
	3	1.63	3.193	1.832
	4	1.96	4.308	2.764
	5	2.20	5.170	3.485
3	1	1.10	1.267	0.326
	2	1.27	1.712	0.869
	3	1.35	1.936	1.143
	4	1.43	2.156	1.412
	5	1.50	2.345	1.642

TABLE 5-continued

Analysis of jet ejector for compression ratio of 1.1.

Area Ratio	Stage	$\frac{P_{outlet}}{P_{inlet}}$	$\frac{P_{motive}}{P_{inlet}}$	$\frac{m_{motive}}{m_{inlet}}$
	6	1.56	2.491	1.821
	7	1.60	2.595	1.948
	8	1.63	2.668	2.036

TABLE 6

Analysis of jet ejector for compression ratio of 1.2.

Area Ratio	Stage	$\frac{P_{outlet}}{P_{inlet}}$	$\frac{P_{motive}}{P_{inlet}}$	$\frac{m_{motive}}{m_{inlet}}$
5	1	1.20	1.848	0.528
	2	1.85	4.596	2.239
	3	2.49	7.306	3.926
	4	2.94	9.215	5.115
4	1	1.20	1.693	0.579
	2	1.69	3.400	2.006
	3	2.01	4.491	2.917
	4	2.24	5.281	3.577
	5	2.36	5.718	3.942
3	1	1.20	1.534	0.652
2	1.53	2.422	1.736	
3	1.58	2.545	1.886	
4	1.61	2.630	1.990	
5	1.63	2.686	2.059	
6	1.65	2.724	2.104	
7	1.66	2.748	2.134	

Table 7 illustrates the mass yield for various embodiments. The results indicate that the method works best when the per-stage compression ratio is small, which requires more stages. Further, the method works best when the area ratio is small, which also requires more stages. More stages allow the inlet pressures and motive pressures to be closely matched, thereby allowing streams with similar velocities to be blended. In some embodiments, extraordinarily high mass yields (kg water/kg steam) are possible.

TABLE 7

Case studies for vapor-compression distillation. ($T_{evaporator}$ = 100° C.)

ΔT (° C.)	Overall Compression Ratio	Per-Stage Compression Ratio	Number of Stages	Area Ratio	Per-Stage Mass Yield (kg water/kg steam)	Overall Mass Yield (kg water/kg steam)
5	1.2	1.03	6	5	119	19.8
				4	190	31.6
				3	425	70.8
		1.05	4	5	37.1	9.3
				4	49.3	12.3
				3	138	34.5
		1.10	2	5	11.1	5.55
				4	11.5	5.75
				3	18.2	9.10
		1.20	1	5	3.58	3.58
				4	3.72	3.72
				3	4.48	4.48

An advantage of utilizing a cascaded arrangement of jet ejectors, such as jet ejector system **50**, is that it blends gas streams of similar pressures; therefore, the velocity of each gas stream is similar. This leads to high efficiencies, even using traditional jet ejectors. Efficiency may be improved further by improving the design of the jet ejector, as is described in further detail below.

FIG. **21** illustrates a jet ejector system **60** according to another embodiment of the invention. In system **60**, a portion of a primary outlet stream **61** from primary jet ejector **62** is bled off and directed to one or more secondary jet ejectors **63**. This is in contrast to system **50** of FIG. **8** in which a portion of primary inlet stream **54** was bled off. The rest of system **60** work in a similar manner to system **50**.

FIG. **22** illustrates a jet ejector system **70** according to another embodiment of the invention. In system **70**, a high-pressure steam, as indicated by reference numeral **71**, that powers the cascade of jet ejectors is produced by drawing a side stream **72** from one of the jet ejectors and compressing it with a suitable mechanical compressor **73**. In this case, the compressor is powered by a suitable steam turbine **74** via shaft **75** The waste steam **76** from turbine **74** may provide motive power to one or more of the jet ejectors, such as primary jet ejector **77**.

FIG. **23** illustrates a jet ejector system **80** according to another embodiment of the invention. System **80** is similar to system **70** except that in system **80** a compressor **81** is powered by a Brayton cycle engine **82** or other suitable engine. A suitable electric motor may also be utilized to power compressor **81**.

FIG. **24** illustrates a jet ejector system **90** according to another embodiment of the invention. In system **90**, multiple compression stages are employed by a plurality of primary jet ejectors **91***a*, **91***b*, **91***c* in series. Each primary jet ejector **91** is supported by its own independent cascade of secondary jet ejectors, which may operate according to one of the embodiments described above in FIGS. **8**, **21**, **22** and/or **23**.

FIG. **25** illustrates a jet ejector system **100** according to another embodiment of the invention. In system **100**, multiple compression stages are employed by a plurality of primary jet ejectors **101***a*, **101***b*, **101***c* in series. However, system **100** differs from system **90** of FIG. **24** in that some of the high-pressure secondary jet ejectors **102** from one cascade are shared with other primary jet ejectors **101** in the series. This reduces the number of secondary jet ejectors, thereby saving capital costs.

FIG. **26** illustrates a jet ejector system **110** according to another embodiment of the invention. In system **110**, multiple compression stages are employed by a plurality of primary jet ejectors **111***a*, **111***b*, **111***c* in series. In this embodiment, only the first primary jet ejector **111***a* in the series includes a cascade **112** of jet ejectors; however, each of the other primary jet ejectors **111***b*, **111***c* receive a stream from one of the secondary jet ejectors from cascade **112** (in this example, secondary jet ejector **112***a*). This again helps reduce the number of jet ejectors, thereby saving capital costs.

FIG. **27** illustrates a jet ejector system **120** according to another embodiment of the invention. In system **120**, multiple compression stages are employed by a plurality of primary jet ejectors **121***a*, **121***b*, **121***c* in series. In this embodiment, only the last primary jet ejector **121***c* in the series includes a cascade **122** of jet ejectors; however, each of the other primary jet ejectors **121***a*, **121***b* receive a stream from one of the secondary jet ejectors from cascade **122** (in this example, secondary jet ejector **122***a*). In addition, secondary jet ejector **122***a* is receiving a portion of outlet stream **124** from primary jet ejector **121***c*.

FIG. **28** illustrates a jet ejector system **130** according to another embodiment of the invention. In system **130**, multiple compression stages are employed by a plurality of primary jet ejectors **131***a*, **131***b*, **131***c* in series. And an equal number of stages of secondary jet ejectors are included in each cascade. The secondary jet ejectors that comprise a particular stage are in series. In this embodiment, the stream for the cascades is drawn from a primary inlet stream **132** of the first primary jet ejector **131***a*.

FIG. **29** illustrates a jet ejector system **140** according to another embodiment of the invention. System **140** is similar to system **130**, except the stream for the cascades is drawn from a primary outlet stream **142** of a primary jet ejector **141***c* in the series.

FIGS. **30** and **31** illustrate jet ejector systems **150**, **160**, respectively, according to other embodiments of the invention. Systems **150**, **160** are similar to systems **130**, **140**, respectively; however, the flow arrangement in systems **150**, **160** obtains a closer match of motive pressures to inlet pressures. Other suitable arrangements of both primary and secondary jet ejectors as well as arrangement of cascades are contemplated by the present invention.

Thus, an advantage of the jet ejector systems described above is that they blend gas streams of similar pressures; therefore, the velocity of each gas stream is similar. This leads to high efficiencies, even using traditional jet ejectors. The efficiency may be improved further by improving the design of the jet ejector, some embodiments of which are described below in conjunction with FIGS. **32** through **41**.

FIGS. **32** through **36** illustrate various embodiments of an improved design of a jet ejector that allows large volumes of motive fluid to be added to propelled gas without obstructing the flow of the propelled gas.

FIG. **32** illustrates a jet ejector **200** according to one embodiment of the invention. Jet ejector **200** may have any suitable size and shape and may be formed from any suitable material. In the illustrated embodiment, jet ejector **200** includes a nozzle **202** having an upstream portion **203**, a downstream portion **204**, and a throat **205** disposed between upstream portion **203** and downstream portion **204**. A plurality of sets of apertures **206** are located in a wall of nozzle **202** in throat **205**, in which the plurality of sets are longitudinally spaced along the wall. Each set of apertures **206** has its apertures circumferentially located around the wall in any suitable pattern and spacing. Apertures **206** may be any suitably shaped apertures. For example, in the illustrated embodiment, apertures are in the form of circumferential slots. Jet ejector **200** also includes a device (not explicitly shown) that is operable to inject a motive fluid **207** through apertures **206** and into a first stream **208** flowing through nozzle **202**. Motive fluid **207** may be any suitable motive fluid, such as gas, vapor, liquid, and may be supplied through an annular space **211** in the wall of nozzle **202**. In such an embodiment, the pressure of motive gas **207** entering each set of apertures **206** is constant. In addition, motive fluid **207** enters first stream **208** at an angle with respect to the flow direction of first stream **208**.

In operation, first stream **208**, which may be any suitable propelled gas, such as low pressure vapor, enters upstream portion **203** of nozzle **202**. Throat **205** then initially accelerates first stream **208** when it enters throat **205**. The motive fluid **207** accelerates first stream **208** even further after entering throat **205** via apertures **206**. To minimize the velocity difference between motive fluid **207** and first stream **208**, it is advantageous to have the upstream most set of apertures **206***a* accelerate first stream **208** first, then the next set of apertures **206***b* accelerate first stream **208** second, and then the next set of apertures **206***c* accelerate first stream **208** last. The size of arrows **212** is meant to illustrate the accelerating of first stream **208** through nozzle **202**.

FIG. **33** illustrates a jet ejector **220** according to another embodiment of the invention. Jet ejector **220** is similar to jet ejector **200**; however, in this embodiment, jet ejector **220** includes sets of apertures **226** in which each successive set of apertures **226** (as their location is farther downstream) is fed with a motive fluid **227** at increasingly higher pressures, which allows motive gas **227** exiting the later set of apertures **206** to have increasingly larger velocities. Thus, set of apertures **226***c* has a greater pressure than set of apertures **226***b*, which has a greater pressure than set of apertures **226***c*. Because a first stream **228** also has increasingly larger velocities, jet ejector **220** minimizes the velocity difference between the two streams, thereby improving efficiency.

FIGS. **34** through **36** illustrates a jet ejector **230** according to another embodiment of the invention. In this embodiment, a motive gas **237** enters a throat **235** of nozzle **232** through multiple point sources **236**, rather than through circumferential slots as in jet ejectors **200**, **220**. Multiple point sources **236** may have any suitable configuration but are preferably small holes or slots. FIG. **35**A is a cross-sectional view through the wall of throat **235** illustrating one of the point sources **236**. FIG. **35**B illustrates a frontal view of the interior wall of throat **235**. As illustrated, point source **236** is coupled to a fan-shaped duct **239** that is defined by walls diverging in a downstream direction in order to introduce motive fluid **237** into throat **235** to entrain first stream **238** (i.e., propelled gas) flowing through nozzle **232**. In one embodiment, fan-shaped duct **239** is a NACA duct. FIG. **36** is a two-dimensional view of the interior wall of nozzle **232** showing a staggered arrangement of multiple fan-shaped ducts **239**. However, the present invention contemplates any suitable arrangement of fan-shaped ducts **239**.

Thus, an advantage of the jet ejectors described in FIGS. **32** through **36** is that they blend gas streams of similar velocities, but do not obstruct the flow of the propelled gas. These jet ejectors may be used in any suitable application, such as compressors, heat pumps, water-based air conditioning, vacuum pumps, and propulsive jets (both for watercraft and aircraft).

FIGS. **37** through **41** illustrate various embodiments of an improved design of a liquid jet ejector that allows motive liquid to be added to the propelled gas without obstructing the flow of the propelled gas. In some embodiments, the motive liquid may be added in stages, which increases efficiency.

FIG. **37** illustrates a liquid jet ejector **250** according to one embodiment of the invention. Liquid jet ejector **250** is similar to jet ejector **200** (FIG. **32**); however, the motive fluid in liquid jet ejector **250** is liquid. In operation, a first stream **258**, which may be any suitable propelled gas, such as low pressure vapor, enters an upstream portion **253** of nozzle **252**. A throat **255** then initially accelerates first stream **258** when it enters throat **255**. The motive fluid **257** accelerates first stream **258** even further after entering throat **255** via nozzles **256**. To minimize the velocity difference between motive fluid **257** and first stream **258**, it is advantageous to have the upstream most set of nozzles **256***a* accelerate first stream **258** first, then the next set of apertures **256***b* accelerate first stream **258** second, and then the next set of apertures **256***c* accelerate first stream **258** last. The size of arrows **251** is meant to illustrate the accelerating of first stream **258** through nozzle **252**. The motive liquid **257** may be supplied via an annular space **259** formed in the wall of nozzle **252**. Alternatively, each nozzle **256** could be supplied by its own pipe. In this embodiment, the pressure of the motive fluid **257** entering each nozzle **256** is constant. Similar to apertures **206** of jet ejector **200**, nozzles **256** may be circumferentially located around the wall in any suitable pattern and spacing.

FIG. **38** illustrates a liquid jet ejector **260** according to one embodiment of the invention. Liquid jet ejector **260** is similar to jet ejector **220** (FIG. **33**); however, the motive fluid in liquid jet ejector **260** is liquid and liquid jet ejector **260** includes nozzles **266** similar to nozzles **256** of liquid jet ejector **250** of FIG. **37**.

FIG. **39** illustrates a liquid jet ejector **270** according to one embodiment of the invention. Liquid jet ejector **270** is similar to liquid jet ejector **250**, except that the motive liquid **277** enters a throat **275** of nozzle **272** through small tubes **276** that are tipped with nozzles. This embodiment facilitates the velocity of motive liquid **277** exiting the nozzles to be parallel to the velocity of a first stream **278** (i.e., the propelled fluid). Any suitable number and arrangement of tubes **276** is contemplated by the present invention.

FIG. **40** illustrates a liquid jet ejector **280** according to one embodiment of the invention. Liquid jet ejector **280** is similar to liquid jet ejector **270** except that the motive liquid **287** enters a throat **285** via tubes **286** at increasingly higher pressures as their location is farther downstream, which allows motive fluid **287** exiting the later set of tubes **286***c* to have increasingly larger velocities. Thus, motive fluid **287** exiting tubes **286***c* has a greater pressure than motive fluid **287** exiting tubes **286***b*, which has a greater pressure than motive fluid **287** exiting tubes **286***a*.

FIG. **41** illustrates a liquid jet ejector **290** according to one embodiment of the invention. Liquid jet ejector **290** includes a plurality of receptacles **291** coupled to the wall of nozzle **292** in order to collect the motive liquid **297**, thereby allowing the liquid to be readily collected and recycled. Receptacles **291** may be any suitable size and shape and are preferably located directly downstream from the nozzles of tubes **296**. The kinetic energy of the exiting liquid converts to pressure at the inlet to the pump, which reduces the required work input to the pump, thereby increasing efficiency. Although FIG. **41** illustrates only one liquid stage along the axial length of nozzle **292**, multiple liquid stages may be employed.

Thus, advantages of the liquid jet ejectors of FIGS. **37** through **41** are as follows: (1) the motive liquid may be added in stages, which increases system efficiency, and (2) the path of the propelled gas may be largely unobstructed by the nozzles that supply the motive liquid. These liquid jet ejectors may be used in any suitable applications, including compressors, heat pumps, water-based air conditioning, vacuum pumps, and vapor compression evaporators. Rather than propelling a gas, they could also be used to propel a liquid. If the outlet area of the jet ejector is less than its inlet area, then it may be used as a propulsive jet for watercraft.

FIGS. **42** through **51** illustrate various embodiments of an evaporator system that incorporates a liquid jet ejector according to various embodiments of the invention.

FIG. **42** illustrates an evaporator system **300** according to one embodiment of the invention. In the illustrated embodiment, system **300** includes a vessel **302** containing a feed **304** having a nonvolatile component (e.g., salt, sugar). The feed **304** may first be degassed by pulling a vacuum on it (equipment not explicitly shown). A liquid jet ejector **306** is coupled to vessel **302** and is operable to receive a vapor from vessel **302**. An example of liquid jet ejector **306** is one marketed by Hijet from Houston, Tex. A pump **308**, which may be driven by a suitable electric motor **310**, is operable to deliver a motive liquid **309** to liquid jet ejector **306**. A knock-out tank **312** is coupled to liquid jet ejector **306** and is operable to separate liquid and vapor received from liquid jet ejector **306** with the aid of a float **313** and a valve **317**.

A heat exchanger **314** is coupled inside vessel **302** and is operable to receive the vapor from knock-out tank **312**, at least some of the vapor condensing within heat exchanger **314**, thereby forming a distilled liquid such as distilled water if the feed is, for example, salt water. The heat of condensation provides the heat of evaporation to vessel **302** to evaporate feed **304**. Concentrated product **315** is removed from vessel **302** via any suitable method. Energy that is added to system **300** may be removed using a condenser **318**. Alternatively, if condenser **318** were eliminated, the energy added to system **300** will increase the temperature of concentrated product **315**. This is acceptable if the product is not temperature sensitive. To remove noncondensibles from system **300**, a small stream is pulled from vessel **302** and passed through a condenser **320**, and then sent to a vacuum pump (not explicitly illustrated).

In system **300**, motive liquid **309** may be a nonvolatile, immiscible, nontoxic, low-viscosity liquid (e.g., silicone oil) or it may be water. If it is water, the water will be in near equilibrium with the vapors discharged from jet ejector **306**. When this water is pumped, it may easily cavitate in pump **308**. In one embodiment, to overcome this problem, knock-out tank **312** is elevated relative to pump **308** so there is no cavitation. Ideally, if the system were perfect, the liquid water could be recycled indefinitely. However, in reality, energy is input into the circulating water (e.g., pump losses, pipe friction). This energy input causes the circulating water to evaporate, so make-up water should be added. In one embodiment, the make-up water is feed water, which has the following benefits: (1) the nonvolatile components increase the fluid density, which improves the efficiency of the jet ejector and (2) the waste thermal energy generated within the circulating fluid causes water to evaporate, which forms more product.

FIG. **43** illustrates an evaporator system **330** according to another embodiment of the invention. System **330** is similar to system **300**, except that a vessel **332** is operated at a higher temperature and pressure than vessel **302**. In system **330**, energy that is added to vessel **332** can cascade through a multi-effect evaporator **334**, which allows additional evaporation to occur. Only three stages are shown in FIG. **43**, but more or less are contemplated by the present invention. Alternatively, a multi-stage flash evaporator could be employed rather than a multi-effect evaporator. In system **330**, noncondensibles may be removed in a manner similar to system **300**. A plurality of sensible heat exchangers **336** may be coupled to vessel **332** and the multi-effect evaporators for heating the feed or for other suitable functions.

FIG. **44** illustrates an evaporator system **340** according to another embodiment of the invention. System **340** is similar to system **300**, except that a pump **342** is driven by a Brayton cycle engine **344** or other suitable engines, such as a Diesel engine or Otto cycle engine. In one embodiment of system **340**, hot engine exhaust **346** is thermally contacted with the feed in the vessel **348**, which produces more product.

FIG. **45** illustrates an evaporator system **350** according to another embodiment of the invention. System **350** is a combination of system **340** (FIG. **44**), but includes a multi-effect evaporator **352**, which allows additional evaporation to occur. Only three stages are shown in FIG. **45**, but more or fewer are contemplated by the present invention. Alternatively, a multi-stage flash evaporator could be employed rather than a multi-effect evaporator.

FIG. **46** illustrates an evaporator system **360** according to another embodiment of the invention. System **360** is similar to system **300** (FIG. **42**), except that a pump **362** is driven by a steam turbine **364**. Steam turbine may be a portion of a Rankine cycle. In this embodiment, the low-pressure steam **365** is sent to a steam jet ejector **366**, such as those described above. Although FIG. **46** illustrates a single steam jet ejector **365**, system **360** may have multiple stages or it may have a cascade steam jet ejector system, such as those described above. Steam jet ejector **366** is in series with a liquid jet ejector **368**. In some embodiments, energy that is added to vessel **361** can cascade through a multi-effect evaporator, which allows additional evaporation to occur, similar to system **330** above.

FIG. **47** illustrates an evaporator system **370** according to another embodiment of the invention. System **370** is similar to system **360** (FIG. **46**), except that the steam jet ejector **372** is in parallel with the liquid jet ejector **374**. As such, steam jet ejector **372** also receives vapor from vessel **376** and compresses it before adding it to the vapor exiting a knock-out tank **378**, which then is sent to a heat exchanger **379** in vessel **376**. In some embodiments, energy that is added to vessel **376** can cascade through a multi-effect evaporator, which allows additional evaporation to occur, similar to system **330** above.

FIG. **48** illustrates an evaporator system **380** according to another embodiment of the invention. System **380** is similar to systems **360** and **370**, except that the waste low-pressure steam **382** from a turbine **384** is sent directly to the primary heat exchanger **386**. In some embodiments, energy that is added to vessel **381** can cascade through a multi-effect evaporator, which allows additional evaporation to occur, similar to system **330** above.

FIG. **49** illustrates an analysis of system **330** using the pump drive mechanism described in system **370**. This analysis illustrates that 1 kg of high-pressure steam fed to the turbine produces 78.2 kg of distilled water. The assumptions follow:

Temperature difference in main heat exchanger=5° C.

Compression ratio=1.2

Number of multi-effect evaporators=8 (three shown in FIG. **49**)

Steam jet ejector per-stage compression ratio=1.03

Steam jet ejector number of stages=6

Steam jet ejector number of cascade levels=3

Steam jet ejector area ratio=5

Liquid jet ejector efficiency=0.75

Pump efficiency=0.85 (appropriate for large industrial pumps)

Steam turbine efficiency=0.8 (relative to isentropic turbine)

The mass ratios shown for the cascade steam jet ejector are based upon the analysis presented above.

The mass flow through the liquid jet ejector is calculated as follows:

$$\text{Steam Through Liquid Jet Ejector} = \frac{\eta_{pump}\eta_{ejector}W_{shaft}}{\hat{H}_{cond} - \hat{H}_{evap}}$$

where $\hat{H}_{cond}$ is the specific enthalpy of the condensing steam (1.2 atm), $\hat{H}_{evap}$ is the specific enthalpy of the evaporating steam (1.0 atm), η_{pump} is the pump efficiency, $\eta_{ejector}$ is the liquid jet ejector efficiency, and W_{shaft} is the shaft work. The shaft work is calculated as follows:

$$W_{shaft}=\eta_{turbine}(\hat{H}_{high}-\hat{H}_{low})m_{steam}$$

where m_{steam} is the mass of high-pressure steam, $\eta_{turbine}$ is the turbine efficiency (compared to isentropic), $\hat{H}_{high}$ is the specific enthalpy of the high-pressure steam from the boiler, and $\hat{H}_{low}$ is the specific enthalpy of the low-pressure steam exiting the turbine. (Note: The conditions at the exit of the turbine correspond to an isentropic expansion.)

FIG. **50** illustrates an analysis similar to the one shown in FIG. **49**. All the assumption are identical, except that the steam jet ejectors use an area ratio of 3, and four cascade levels are employed. In this scenario, 1 kg of high-pressure steam produces 93.4 kg of distilled water.

FIG. **51** illustrates an analysis similar to the one shown in FIGS. **49** and **50**, except that no steam jet ejector is employed. The waste steam from the turbine is directly sent to the condensing side of the primary heat exchanger. In this case, 1 kg of high-pressure steam produces 75.5 kg of distilled water, which is nearly identical to the case shown in FIG. **49**, but not quite as good as the case presented in FIG. **50**. This illustrates that there may be a benefit of using the jet ejectors only if they are very efficient (i.e., low area ratio with many stages).

The following table compares various options:

Option	Energy (kJ/kg distilled water)	Effects*
Single-effect evaporator (100° C.)	2,256.58	1
FIG. 51	39.11	57.7
FIG. 49	37.80	59.7
FIG. 50	31.96	70.6
FIG. 44 (engine efficiency = 30%)	40.99	55.1
FIG. 44 (engine efficiency = 40%)	30.75	73.4
FIG. 44 (engine efficiency = 50%)	24.60	91.7
FIG. 44 (engine efficiency = 60%)	20.50	110.1
FIG. 45 (engine efficiency = 30%, 8 stages)	37.29	60.5
FIG. 45 (engine efficiency = 40%, 8 stages)	28.44	79.4
FIG. 45 (engine efficiency = 50%, 8 stages)	23.01	98.1
FIG. 45 (engine efficiency = 60%, 8 stages)	19.32	116.8

*Effect = Energy of single-effect evapor/Energy of the option

This table illustrates that a simple liquid jet ejector combined with a high-efficiency engine (FIGS. **44** and **45**) may be the most attractive option. However, high-efficiency engines often require premium fuels, which can be expensive. The steam-turbine systems (FIG. **46** through **48**) may use low-cost fuels (e.g., coal), and may be the most economical system in some situations.

An advantage is it uses a high-efficiency liquid jet ejector in a cost-effective dewatering system. When combined with steam jet ejectors and multi-effect evaporators, any energy inefficiencies of the liquid jet system (liquid jet itself, pump, turbine) produce heat that usefully distills liquid. This liquid jet ejector may be used in water-based air conditioning.

FIGS. **52** through **55** illustrate various embodiments of an improved design of a vapor-compression evaporator system. Some important features of the improved designs are (1) compressor equipment may be smaller due to lower vapor throughput, and (2) the systems may be tuned to the operating regions where the compressors are most efficient.

FIG. **52** illustrates a vapor-compression evaporator system **400** according to one embodiment of the invention. In the illustrated embodiment, system **400** includes a plurality of vessels **402***a-c* in series to form a multi-effect evaporator system. Each vessel contains a feed **404** having a nonvolatile component (e.g., salt, sugar). The feed **404** may first be degassed by pulling a vacuum on it (equipment not explicitly shown). A liquid jet ejector **406** is coupled to the last vessel in the series (**402***c*) and is operable to receive a vapor therefrom. An example of liquid jet ejector **406** is one marketed by Hijet from Houston, Tex. A pump **408** is operable to deliver a motive liquid **410** to the liquid jet ejector **406** for compressing the vapors pulled from the coldest evaporator stage, vessel **402***c*. A knock-out tank **412** is coupled to liquid jet ejector **406** and is operable to separate liquid and vapor received from liquid jet ejector **406**. A plurality of heat exchangers **414***a-c* are coupled inside respective vessels **402***a-c*. Heat exchanger **414***a* is operable to receive the vapor from knock-out tank **412**, at least some of the vapor condensing therein, whereby the heat of condensation provides the heat of evaporation to vessel **402***a*. At least some of the vapor inside vessel **402***a* is delivered to heat exchanger **414***b*, whereby the condensing, evaporating, and delivering steps continue until the last vessel in the series is reached (in this embodiment, vessel **402***c*).

In FIG. **52**, only three stages are shown (i.e., three vessels **402**); however, more or fewer could be used. Concentrated product **416** may be removed from each of the vessels **402**. Energy that is added to system **400** may be removed using a suitable condenser **418**. Alternatively, if condenser **418** were eliminated, the energy added to system **400** will increase the temperature of concentrated product **416**. This is acceptable if the product is not temperature sensitive. To remove noncondensibles from system **400**, a small stream is pulled from each vessel **402** and passed through a suitable condenser **419** and is sent to a vacuum pump (not shown).

In system **400**, motive liquid **410** may be a nonvolatile, immiscible, nontoxic, low-viscosity liquid (e.g., silicone oil) or it may be water. If it is water, the water will be in near equilibrium with the vapors discharged from jet ejector **406**. When this water is pumped, it may easily cavitate in pump **408**. In one embodiment, to overcome this problem, knock-out tank **412** is elevated relative to pump **408** so there is no cavitation. Ideally, if the system were perfect, the liquid water could be recycled indefinitely. However, in reality, energy is input into the circulating water (e.g., pump losses, pipe friction). This energy input causes the circulating water to evaporate, so make-up water should be added. In one embodiment, the make-up water is feed water, which has the following benefits: (1) the nonvolatile components increase the fluid density, which improves the efficiency of the jet ejector and (2) the waste thermal energy generated within the circulating fluid causes water to evaporate, which forms more product.

FIG. **53** illustrates a vapor-compression evaporator system **430** according to another embodiment of the invention. System **430** is similar to system **400** above, except that the vapor-compression evaporator vessels **432** are operated at a higher temperature and pressure than in system **400**. In system **430**, energy that is added to the vapor-compression evaporator vessels **432** may cascade through a multi-effect evaporator **434** (three stages shown), which allows additional evaporation to occur. Alternatively, a multi-stage flash evaporator may be employed rather than a multi-effect evaporator. In system **430**, noncondensibles may be removed in a manner similar to system **400**.

FIG. **54** illustrates a vapor-compression evaporator system **440** according to another embodiment of the invention. System **440** is similar to system **400** above, except that the vapors are compressed using a mechanical compressor **442** driven by a suitable electric motor **443**. To reduce the superheat in compressor **445**, and thereby increase its efficiency, atomized liquid water **444** is added to compressor **445**. Preferably, the liquid water is feed water; as water evaporates from the feed water as it removes the heat of compression, it creates more distilled water and a concentrated product. Alternatively, if the compressor materials do not tolerate the nonvolatile components (e.g., salt) in the circulating cooling liquid **444**, then the cooling liquid **445** could be distilled water.

FIG. **55** illustrates a vapor-compression evaporator system **450** according to another embodiment of the invention. System **450** is similar to systems **440** except that energy that is added to vapor-compression evaporators **452** may cascade through a multi-effect evaporator **454**, which allows additional evaporation to occur, similar to system **430** above.

Thus, advantages of the vapor-compression evaporator systems of FIGS. **52** through **55** are 1) because the vapor flow through the compressors is smaller, the compressors may be smaller than the compressors described in the evaporator systems above; and 2) the compression ratio may be adjusted so the compressor operates in its most efficient range. This is particularly important for a liquid jet ejector, which has lower efficiency at lower compression ratios.

Referring now to FIGS. **56** through **61**, in general, a heat exchanger is provided that includes a shell and a sheet assembly disposed within the shell. The sheet assembly may include a number of substantially parallel rectangular sheets configured such that they define first passageways extending generally in a first direction and second passageways extending generally in a second direction perpendicular to the first direction. The sheet assembly may be configured such that communicating a first fluid through the first passageways and communicating a second fluid through the second passageways causes heat transfer between the first and second fluids. For example, the first fluid may comprise high pressure steam and the second fluid may comprise a liquid solution (such as saltwater, seawater, concentrated fermentation broth, or concentrated brine, for example) such that communicating the high-pressure steam and the liquid solution through the first and second passageways, respectively, causes at least a portion of the high-pressure steam to condense and at least a portion of liquid solution to boil off.

FIG. **56** illustrates a cross-section of an example heat exchanger assembly **500** including a shell **510** and a sheet assembly **512** disposed within shell **510** in accordance with an embodiment of the invention. Shell **510** may comprise any suitable shape and may be formed from any suitable material for housing pressurized gasses and/or liquids. For example, in the embodiment shown in FIG. **56**, shell **510** comprises a substantially cylindrical portion **516** and a pair of hemispherical caps (not expressly shown) coupled to each end of cylindrical portion **516**. The cross-section shown in FIG. **56** is taken at a particular point along the length of cylindrical portion **516**, which length extends in a direction perpendicular to the page.

In general, heat exchanger assembly **500** is configured to allow at least two fluids to be communicated into shell **510**, through passageways defined by sheet assembly **512** (such passageways are illustrated and discussed below with reference to FIG. **57**A) such that heat is transferred between the at least two fluids, and out of shell **510**. Shell **510** may include any number of inlets and outlets for communicating fluids into and out of shell **510**. In the embodiment shown in FIG. **56**, shell **510** includes a first inlet **520**, a first outlet **522**, a second inlet **524**, a second outlet **526** and a third outlet **528**. First inlet **520** and first outlet **522** are configured to communicate a first fluid **530** into and out of shell **510**. Second inlet **524**, second outlet **526**, and third outlet **528** are configured to communicate a second fluid **532** into and out of shell **510**.

Due to the transfer of heat between first fluid **530** and second fluid **532**, at least a portion of first fluid **530** and/or second fluid **532** may change state within shell **510** and thus exit shell **510** in a different state than such fluids **530** and/or **532** entered shell **510**. For example, in a particular embodiment, relatively high-pressure steam **534** enters shell **510** through first inlet **520**, enters one or more first passageways within sheet assembly **512**, becomes cooled by a liquid **540** flowing through one or more second passageways adjacent to the one or more first passageways within sheet assembly **512**, which causes at least a portion of the steam **534** to condense to form steam condensate **536**. The steam condensate **536** flows toward and through first outlet **522**. Concurrently, liquid **540** (saltwater, seawater, concentrated fermentation broth, or concentrated brine, for example) enters shell **510** through second inlet **524**, enters one or more second passageways within sheet assembly **512**, becomes heated by steam **534** flowing through the one or more first passageways adjacent to the one or more second passageways within sheet assembly **512**, which causes at least a portion of the liquid **540** to boil to form relatively low pressure steam **542**. The low pressure steam **542** escapes from shell **510** through second outlet **526**, while the unboiled remainder of liquid **540** flows toward and through third outlet **528**.

In some embodiments, heat exchanger assembly **500** includes one or more pumps **550** operable to pump liquid **540** that has exited shell **510** through third outlet **528** back into shell **510** through second inlet **524**, as indicated by arrows **552**. Pump **550** may comprise any suitable device or devices for pumping a fluid through one or more fluid passageways. As shown in FIG. **56**, liquid **540** may be supplied to the circuit through a feed input **554**. In embodiments in which liquid **540** comprises a solution (such as a seawater solution, for example), a relatively dilute form of such solution (as compared with the solution exiting shell **510** through third output **528**) may be supplied through feed input **554**. In addition, a portion of liquid **540** being pumped toward second inlet **524** of shell **510** may be redirected away from shell **510**, as indicated by arrow **556**. In embodiments in which liquid **540** comprises a solution (such as a seawater solution, for example), such redirected liquid **540** may comprise a relatively concentrated form of such solution (as compared with the diluted solution supplied through feed input **554**). Although inlets **520**, **524** and outlets **522**, **526** and **528** are described herein as single inlets and outlets, each inlet **520**, **524** and each outlet **522**, **526** and **528** may actually include any suitable number of inlets or outlets.

Heat exchanger assembly **500** may also include a plurality of mounting devices **560** coupled to shell **510** and operable to mount sheet assembly **512** within shell **510**. Each mounting device **560** may be associated with a particular corner of sheet assembly **512**. Each mounting device **560** may be coupled to shell **510** in any suitable manner, such as by welding or using fasteners, for example. In the embodiment shown in FIG. **56**, each mounting device **560** comprises a Y-shaped bracket into which a corner of sheet assembly **512** is mounted. Each mounting device **560** may extend along the length of shell **510**, or at least along the length of a portion of shell **510** in which fluids **530** and **532** are communicated, in order to create two volumes within shell **510** that are separated from each other. A first volume **564**, which includes regions generally to the left and right of sheet assembly **510**, as well as one or more first passageways defined by sheet assembly **510** (such first passageways are illustrated and discussed below with reference to FIG. **57**A), is used to communicate first fluid **530** through heat exchanger assembly **500**. A second volume **566**, which includes regions generally above and below sheet assembly **510**, as well as one or more second passageways defined by sheet assembly **510** (such second passageways are illustrated and discussed below with reference to FIG. **57**A), is used to communicate second fluid **532** through heat exchanger assembly **500**.

Since first volume **564** is separated from second volume **566** by the configuration of sheet assembly **512** and mounting devices **560**, first fluid **530** is kept separate from second fluid **532** within shell **510**. In addition, one or more gaskets **562** may be disposed between each Y-shaped bracket **560** and its corresponding corner of sheet assembly **512** to provide a seal between first volume **564** and second volume **566** at each corner of sheet assembly **512**. Gaskets **562** may comprise any suitable type of seal or gasket, may have any suitable shape (such as having a square, rectangular or round cross-section, for example) and may be formed from any material suitable for forming a seal or gasket.

Heat exchanger assembly **500** may also include one or more devices for sliding, rolling, or otherwise positioning sheet assembly **512** within shell **510**. Such devices may be particularly useful in embodiments in which sheet assembly **512** is relatively heavy or massive, such as where sheet assembly **512** is formed from metal. In the embodiment shown in FIG. **56**, heat exchanger assembly **500** includes wheels **568** coupled to sheet assembly **512** that may be used to roll sheet assembly **512** into shell. Wheels **568** may be aligned with, and roll on, wheel tracks **570** coupled to shell **510** in any suitable manner.

FIG. **57**A illustrates a three-dimensional view of sheet assembly **512** of heat exchanger assembly **500** in accordance with one embodiment of the invention. Sheet assembly **512** includes a plurality of sheets **580** configured and coupled to each other to form a plurality of first passageways **582** extending in a first direction **584** alternating with a plurality of second passageways **586** extending in a second direction **588** perpendicular to the first direction **584**. Each passageway **582** and **586** is substantially defined by an adjacent pair of sheets **580**. In this embodiment, sheets **580** are aligned substantially parallel and, when positioned within shell **510**, the major surface of each sheet **580** extends in a plane substantially perpendicular to the direction of the length of cylindrical portion **516** of shell **510**.

As discussed above with reference to FIG. **56**, first passageways **582** form a portion of first volume **564** and are thus used to communicate first fluid **530**, while second passageways **586** form a portion of second volume **566** and are thus used to communicate second fluid **532**. As fluids **530** and **532** pass through alternating first passageways **582** and second passageways **586**, respectively, heat is transferred from the higher temperature fluid **530** or **532** to sheets **580**, and then from sheets **580** to the lower temperature fluid **530** or **532**. In this manner, heat is transferred between fluids **530** and **532** via sheets **580**.

In the embodiments shown in FIG. **57**A, each sheet **580** has a substantially square shape having four edges **590**. In other embodiments, sheets **580** may comprise any suitable shape and configuration. For example, sheets **580** may have a generally rectangular, hexagonal, circular, or other geometric shape. In order to define alternating passageways **582** and **586**, each sheet **580** is coupled to an adjacent sheet **580** on one side at two of the four edges **590** and to an adjacent sheet **580** on the other side at the other two of the four edges **590**. For example, sheet **580***a*, which is positioned between adjacent sheet **580***b* and adjacent sheet **580***c*, is coupled to adjacent sheet **580***b* at opposite edges **590***a* and **590***b* of sheet **580***a*, and is coupled to adjacent sheet **580***c* at opposite edges **590***c* and **590***d* of sheet **580***a*.

Sheets **580** may be coupled to each other at edges **590** in any suitable manner, as discussed in greater detail below with reference to FIG. **59**. In the embodiment shown in FIG. **57**A, each sheet **580** is folded near each edge **590** to form flanges **592** at each edge **590** which are then coupled to corresponding flanges **592** of adjacent sheets **580**. FIG. **57**B is a blown-up view of a corner area of sheet assembly **512**, illustrating flanges **592** of adjacent sheets **580** being coupled to each other in accordance with an embodiment of the invention. As shown in FIG. **57**B, sheet **580***a* is folded twice at approximately 90 degree angles to form a flange **592***a* including a first flange portion **594***a* and a second flange portion **596***a*. First flange portion **594***a* forms an approximately 90 degree angle with the major portion of sheet **580***a*, indicated as **598***a*, and second flange portion **596***a* forms an approximately 90 degree angle with first flange portion **594***a*. Thus, the surface of second flange portion **596***a* is approximately parallel with the surface of major portion **598***a* of sheet **580***a*. A triangular flap **600***a* is folded from first flange portion **594***a* and may be affixed to second flange portion **596***a* (such as by welding, for example). Similarly, sheet **580***b* is folded twice at approximately 90 degree angles to form a flange **592***b* including a first flange portion **594***b* and a second flange portion **596***b*. First flange portion **594***b* forms an approximately 90 degree angle with the major portion of sheet **580***b*, indicated as **598***b*, and second flange portion **596***b* forms an approximately 90 degree angle with first flange portion **594***b*. Thus, the surface of second flange portion **596***b* is approximately parallel with the surface of major portion **598***b* of sheet **580***b*. A triangular flap **600***b* is folded from first flange portion **594***b* and may be affixed to second flange portion **596***b* (such as by welding, for example).

FIG. **57**C illustrates a side view of the corner of sheet assembly **512** illustrated in FIG. **57**B.

FIGS. **58**A-**58**B illustrate an example method of forming a particular sheet **580***a*, including flanges **592**, of sheet assembly **512** in accordance with one embodiment of the invention. FIG. **58**A illustrates a generally flat sheet **610** of material, such as sheet metal or one or more polymers, for example. The sheet **610** has a generally square shape including one or more notches removed from each corner. Cuts **612** are formed in each corner at approximately 45 degrees relative to the edges **590** of sheet **610** in order to form triangular flaps **600** in the resulting sheet **580***a*. From sheet **610** formed as shown in FIG. **58**A, flanges **592***a* are formed by folding sheet **610** at each fold line **614** (indicated in FIG. **58**A by dashed lines) at approximately 90 degree angles. For example, flange **592***a* may be formed by (a) folding the edge portion **590***a* of sheet **610** approximately 90 degree inward (out of the page and toward the center of sheet **610**) at fold line **614***a* to form first flange portion **594***a*, and (b) folding the remaining edge portion **590***a* of sheet **610** approximately 90 degree outward (to the left and down toward the page) at fold line **614***b* to form second flange portion **596***a*. Thus, the resulting flange **592***a* extends generally out of the page. The flange **592** at opposing edge **590***b* may be formed in the same manner as flange **592***a*. The flanges **592** at edges **590***c* and **590***d* may be formed in a similar, but opposite, manner such that the flanges **592** at edges **590***c* and **590***d* extend generally into the page. Triangular flaps **600** may then be folded down and connected (such as by welding) to second flange portions **596** to reinforce each flange **592**. For example, triangular flap **600***a* may be folded down and welded to second flange portion **596***a* to reinforce flange **592***a*.

FIG. **58**B illustrates the resulting sheet **580***a*, including flanges **592** at each edge **590***a*-**590***d* of sheet **580***a*. Flanges **592** at edges **590***a* and **590***b* of sheet **580***a* extend in a first direction (out of the page), such that they may be coupled to flanges **592** of adjacent sheet **580***b*, while flanges **592** at edges **590***c* and **590***d* of sheet **580***a* extend in the opposite direction (into the page), such that they may be coupled to flanges **592** of adjacent sheet **580***c*.

Sheets **580** may also include one or more protrusions for preventing passageways **582** or **586** between adjacent sheets **580** from being cut off, such as due to the distortion of sheets **580** during operation of heat exchanger apparatus **500** (such as due to the presence of high-pressure fluids, for example) and/or to provide additional strength or stiffening to sheets **580**. In the embodiment shown in FIGS. **58**A-**58**B, sheet **580***a* includes a plurality of stiffening ribs, or corrugations, **620** which strengthen sheet **580***a*, as well as ensure that the second passageway **586** between sheets **580***a* and **580***b* remains intact during the operation of heat exchanger apparatus **500**. Sheet **580***b* may also include a plurality of stiffening ribs (not expressly shown) operable to engage stiffening ribs **620** of sheet **580***a*. In a particular embodiment, such stiffening ribs of sheet **580***b* are oriented in a direction perpendicular to that of stiffening ribs **620** of sheet **580***a*.

FIG. **58**C illustrates a cross-sectional view of sheet **580***a* taken along Cut A shown in FIG. **58**B. FIG. **58**D illustrates a cross-sectional view of sheet **580***a* taken along Cut B shown in FIG. **58**B. Taken together with FIG. **58**B, FIGS. **58**C and **58**D illustrate that, as discussed above, flanges **592** at edges **590***a* and **590***b* of sheet **580***a* extend in a first direction (out of the page), while flanges **592** at edges **590***c* and **590***d* of sheet **580***a* extend in the opposite direction (into the page).

As discussed above, in forming sheet assembly **512**, second flange portion **596***a* of flange **592***a* of sheet **580***a* may be coupled to second flange portion **596***b* of flange **592***b* of sheet **580***b* in any suitable manner. FIG. **59** illustrates various example manners in which second flange portion **596***a* may be coupled to second flange portion **596***b*. As shown in FIG. **59**, second flange portion **596***a* may be coupled to second flange portion **596***b* by a weld **630**; a brazed connection **632**; a crimp clamp **634**; one or more fasteners **636**, such as a rivet or screw for example; or a crimp connection **638**, for example. For some types of couplings, a gasket **640** may be inserted in order to assure a seal between second flange portion **596***a* and second flange portion **596***b* (and thus a seal between sheets **580***a* and **580***b* at the relevant edge of **580***a* and **580***b*). In embodiments in which one or more fasteners **636** are used, stiffeners **642** may be provided to strengthen or reinforce the connection.

As discussed above, sheets **580** may be formed from any suitable material, such as sheet metal or one or more polymers, for example. Table 1 compares various polymers that could be used for the sheet-polymer assemblies. The underlined value in Table 1 is used to calculate the overall heat transfer coefficient, U, which is determined as follows:

$$U = \left[\frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o}\right]^{-1}$$

where

h_i=inside heat transfer coefficient

=3000 Btu/(h·ft^2·° F.) (for boiling water)

h_o=outside heat transfer coefficient

=15,000 Btu/(h·ft^2·° F.) (dropwise condensation for polymer)

=2,000 Btu/(h·ft^2·° F.) (filmwise condensation for metal)

k=thermal conductivity of material (Btu/(h·ft·° F.)

x=material thickness

=0.01 in=500 mil=0.00083 ft

The overall heat transfer coefficient U is reported in the fifth column of Table 1. The cost of each polymer per square foot, C, is shown in the fourth column of Table 1. The ratio U/C is reported in the sixth column of Table 1, which is the overall heat transfer coefficient on a dollar basis, rather than an area basis. The ratio U/C may be referred to as the "figure of merit." The polymers are listed in order, with the highest U/C appearing at the top and the lowest U/C appearing at the bottom. In the last column of Table 1, the U/C for each polymer is compared to that of stainless steel (SS) and titanium (Ti). Stainless steel resists corrosion for many solutions (e.g., sugar, calcium acetate), but titanium may be used for particularly corrosive solutions, such as seawater, for example.

The polymer with the highest U/C is HDPE (high-density polyethylene). Polypropylene is also very good, and it may perform well at slightly higher temperatures. Other polymers (polystyrene, PVC) may also be considered, but their U/C performance may not be quite as good as polyethylene or polypropylene. As a general rule, the thermal conductivity of the polymers is much lower than metals, but their U/C performance may be superior because of their low material cost relative to metals. In addition, polymers are typically less expensive to form into the final shape of sheets **580** and sheet assembly **512** than metals. Further, polymer structures may be easier to seal, providing an additional benefit over metals.

HDPE has a thermal conductivity comparable to stainless steel if the polymer molecules are aligned in the direction of heat flow (see third column, first row, Table 1). FIG. **60**A illustrates an example method of aligning the molecules in a sample **650** of HDPE by drawing the polymer melt through a die **652**. The shear orients the HDPE molecules in the flow direction, thus forming a molecularly-oriented HDPE block **654**. By cutting polymer sheets **656** from such molecularly-oriented HDPE block **554** in which the molecules are aligned perpendicular to the sheet surface **658**, the heat transfer performance of the HDPE sheet may be increased or maximized.

In some situations, the desired size of sheets **580** for a sheet assembly **512** may be larger than the molecularly-oriented polymer (e.g., HDPE) block **654** that may be produced due to available manufacturing equipment, equipment limitations, cost or some other reason. FIG. **60**B illustrates a method of forming a sheet **580** (e.g., a relatively large sheet **580**) by joining a number of polymer sheets **656**. Such polymer sheets **656** may be joined in any suitable manner to form sheet **580**, such as welding or heating to a relatively low temperature, for example.

In addition to providing increased heat transfer per cost as compared with metal, polymers may be more corrosion-resistant, more pliable, and more easily formed into sheets **580** and sheet assembly **512**.

TABLE 1

Comparison of polymers.

Material	Max. Working Temp. ° F.	k Thermal Conductivity Btu/(h · ft · ° F.)	C $/ft² (10 mil thickness)	U[b] Btu/ (h · ft² · ° F.)	U/C Btu/ (h · $ · ° F.)	(U/C)plastic / (U/C)metal
HDPE (high-density polyethylene)	160[c] 175-250[e]	0.29[i] 0.25 @ 70° F.[k] 0.20 @ 212° F.[k] 4.9-8.1[m]	0.12[a] 0.11[d]	220	2,000	2.64 (SS) 5.93 (Ti)
LDPE (low-density polyethylene)	185-214[d] 180-212[e]	0.19i 0.17-0.24[j] 0.20 @ 70° F.[k] 0.14 @ 212° F.[k]	0.10[d]	158	1,500	1.98 (SS) 4.45 (Ti)
Polypropylene	225[d] 225-300[e]	0.12[i] 0.083-0.12[j] 0.12 @ 70° F.[k] 0.11 @ 212° F.[k]	0.09[a] 0.10[d]	126	1,400	1.84 (SS) 4.15 (Ti)
HIPS (high-impact polystyrene)	190[c] 140-175[e]	0.083[l]	0.09[a]	104	1,156	1.52 (SS) 3.43 (Ti)
Ultra-high MW polyethylene	180[d]	0.24[r]	0.50[a] 0.25[d]	260	1,037	1.37 (SS) 3.08 (Ti)
PVC (polyvinyl chloride)	140[d] 150-175[e]	0.11[j] 0.10[k]	0.14[d]	126	900	1.19 (SS) 2.67 (Ti)
Acrylic	209[c] 180[d] 175-225[e]	0.12[j]	0.28[a] 0.40[d]	137	489	0.64 (SS) 1.45 (Ti)
ABS	180[c] 185[d] 160-200[e]	0.074-0.11[p]	0.62[a] 0.52[d]	126	242	0.32 (SS) 0.72 (Ti)
Acetal	280[c] 195[e]	0.25 @ 70° F.[k] 0.21 @ 212° F.[k]	1.03[d]	230	223	0.29 (SS) 0.66 (Ti)
PET (polyethylene terephalate)	230[d] 175[e]	0.08[w]	0.54[d]	93	172	0.23 (SS) 0.51 (Ti)
PBT (polybutylene teraphalate polyester, Hydex)	240[f]	0.17[t]	1.21[a]	189	156	0.21 (SS) 0.46 (Ti)
CPVC	215[d] 230[e]	0.08[q]	1.92[a] 0.74[d]	93	125	0.17 (SS) 0.37 (Ti)
Noryl (polyphenylene oxide)	175-220[e]	0.11[s]	1.07[a]	126	117	0.15 (SS) 0.35 (Ti)
Polycarbonate	280[o] 190[d] 250[e]	0.13 @ 70° F.[k] 0.14 @ 212° F.[k]	1.86[a]	158	85	0.11 (SS) 0.25 (Ti)
Teflon	500[d] 550[e]	0.14[j]	2.35[a] 2.21[d]	158	71	0.094 (SS) 0.21 (Ti)
Polysulfone	3400 300[e]	0.15[u]	3.42[a]	169	49	0.065 (SS) 0.15 (Ti)
Polyurethane		0.13[v]	3.25[a]	147	45	0.060 (SS) 0.13 (Ti)
Nylon	230[d] 180-300[e]	0.14[j]	6.45[a]	158	24	0.032 (SS) 0.071 (Ti)
PEEK	480[d]	0.15[q]	25.49[a]	168	6.6	0.009 (SS) 0.02 (Ti)
Stainless Steel		9.4[y]	1.68[g] 1.49[d] 1.43[n]	1,085	759	1.00 (SS)
Titanium		12[x]	7.4[h] 3.29[o]	1,108	337	1.00 (Ti)

[a]K-mac Plastics (www.k-mac-plastics.net)
[b]h_i = 3000 BtU/(h · ft² · ° F.) h_o = 15,000 BtU/(h · ft² · ° F.) (dropwise condensation for plastic) h_o = 2,000 BtU/(h · ft² · ° F.) (filmwise condensation for metal) $h_m = k/x$ x = 0.01 in = 0.00083 ft
[c]Hubert Interactive
[d]McMaster-Carr
[e]Perry's Handbook of Chemical Engineering (Table 23-22)
[f]K-mac Plastics
[g]www.metalsdepot.com
[h]www.halpemtitanium.com
[i]R. M. Ogorkiewicz, Thermoplastics: Properties and Design, Wiley, London (1974) p. 133-135
[j]R. M. Ogorkiewicz, Engineering Properties of Thermoplastics, Wiley, London (1970)
[k]P. e. Powell, Engineering with Polymers, Chapman and Hall, London (1983), p. 242
[l]Building Research Institute, Plastics in Building, National Academy of Sciences, 1955.

TABLE 1-continued

Comparison of polymers.

Material	Max. Working Temp. ° F.	k Thermal Conductivity Btu/(h · ft · ° F.)	C $/ft² (10 mil thickness)	U[b] Btu/ (h · ft² · ° F.)	U/C Btu/ (h · $ · ° F.)	$\frac{(U/C)_{plastic}}{(U/C)_{metal}}$

[m]In the direction of molecular orientation, draw direction ratio of 25 www.electronics-cooling.com/html/2001_august_techdata.html Choy C. L., Luk W. H., and Chen, F. C., 1978, Thermal Conductivity of Highly Oriented Polyethylene, Polymer, Vol. 19, pp. 155-162.
[n]Rickard Metals, rickardmetals.com ($3.50/lb)
[o]Astro Cosmos, 888-402-7876 ($14/lb, Grade 2)
[p]3d-cam.com
[q]boedeker.com
[r]bayplastics.co.uk
[s]sdplastics.com
[t]tstar.com
[u]plasticsusa.com
[v]zae-bayern.de
[w]toray.fr
[x]efunda.com
[y]Perry's Handbook of Chemical Engineering (Table 3-322)

FIGS. **61**A-**61**D illustrates another example sheet assembly **512**A in accordance with another embodiment of the invention. FIG. **61**A illustrates a three-dimensional view of sheet assembly **512**A. FIG. **61**B is a blown-up view of a corner area of sheet assembly **512**A, illustrating flanges **592**A of adjacent sheets **580**A being coupled to each other in accordance with an embodiment of the invention. FIG. **61**C illustrates a side view of the corner of sheet assembly **512**A illustrated in FIG. **61**B. FIG. **61**D illustrates the configuration of a flat sheet **610**A of material, such as sheet metal or one or more polymers, for example, that may be used to form each sheet **580**A of sheet assembly **512**A (such as by folding sheet **610**A, such as described above with regard to FIGS. **3**A-**3**B). As shown in FIGS. **61**A-**61**D, sheet assembly **512**A is substantially similar to sheet assembly **512** shown in FIG. **57**A. However, unlike sheet assembly **512**, sheet assembly **512**A does not include triangular flaps **600** at the corners of each sheet **580**A. Thus, sheet assembly **512**A may be more simple to construct, and thus less expensive, than sheet assembly **512**.

Although embodiments of the invention and their advantages are described in detail, a person skilled in the art could make various alterations, additions, and omissions without departing from the spirit and scope of the present invention.

What is claimed is:

1. A vapor-compression evaporation system, comprising:

a vessel containing a feed having a nonvolatile component;

a liquid jet ejector coupled to the vessel and operable to receive a vapor from the vessel;

a pump operable to deliver a motive liquid to the liquid jet ejector;

a tank coupled to the liquid jet ejector and operable to separate liquid and vapor received from the liquid jet ejector;

a heat exchanger coupled inside the vessel and operable to receive the vapor from the tank, at least some of the vapor condensing within the heat exchanger, thereby forming distilled liquid; and

whereby the heat of condensation provides the heat of evaporation to the vessel to evaporate the feed.

2. The vapor-compression evaporation system of claim **1**, further comprising a multi-effect evaporator for additional evaporation of the feed.

3. The vapor-compression evaporation system of claim **1**, further comprising a multi-stage flash evaporator for additional evaporation of the feed.

4. The vapor-compression evaporation system of claim **1**, further comprising an engine operable to drive the pump.

5. The vapor-compression evaporation system of claim **4**, wherein waste heat from the engine is delivered to the vessel.

6. The vapor-compression evaporation system of claim **2**, further comprising an engine operable to drive the pump.

7. The vapor-compression evaporation system of claim **6**, wherein waste heat from the engine is delivered to the vessel and the multi-effect evaporator.

8. The vapor-compression evaporation system of claim **1**, further comprising:

a steam turbine operable to drive the pump; and

a steam jet ejector coupled between the tank and the vessel, the steam jet ejector driven by low-pressure steam from the steam turbine and working in series with the liquid jet ejector.

9. The vapor-compression evaporation system of claim **1**, further comprising:

a steam turbine operable to drive the pump; and

a steam jet ejector coupled to the vessel, the steam jet ejector driven by waste steam from the steam turbine and working in parallel with the liquid jet ejector.

10. The vapor-compression evaporation system of claim **1**, further comprising a steam turbine operable to drive the pump and operable to deliver waste steam to the heat exchanger.

11. The vapor-compression evaporation system of claim **1**, wherein the nonvolatile component is selected from the group consisting of salt and sugar.

12. A vapor-compression evaporation system, comprising:

a plurality of vessels in series each containing a feed having a nonvolatile component;

a liquid jet ejector coupled to the last vessel in the series and operable to receive a vapor from the last vessel in the series;

a pump operable to deliver a motive liquid to the liquid jet ejector;

a tank coupled to the liquid jet ejector and operable to separate liquid and vapor received from the liquid jet ejector;

a plurality of heat exchangers coupled inside respective ones of the vessels, the heat exchanger in the first vessel in the series operable to receive the vapor from the tank, at least some of the vapor condensing therein, whereby the heat of condensation provides the heat of evaporation to the first vessel in the series; and

wherein at least some of the vapor inside the first vessel in the series is delivered to the heat exchanger in the next vessel in the series, whereby the condensing, evaporating, and delivering steps continue until the last vessel in the series is reached.

13. The vapor-compression evaporation system of claim **12**, further comprising a multi-effect evaporator coupled to the last vessel in the series for additional evaporation of the feed.

14. The vapor-compression evaporation system of claim **12**, further comprising a multi-stage flash evaporator coupled to the last vessel in the series for additional evaporation of the feed.

15. The vapor-compression evaporation system of claim **12**, wherein the nonvolatile component is selected from the group consisting of salt and sugar.

16. The vapor-compression evaporation system of claim **12**, further comprising a condenser coupled to the last vessel in the series for removing energy from the last vessel in the series.

17. The vapor-compression evaporation system of claim **12**, further comprising a plurality of devices coupled to respective ones of the vessels for removing concentrated feed from respective ones of the vessels.

18. The vapor-compression evaporation system of claim **12**, wherein the pump is driven by a device selected from the group consisting of an engine, a steam turbine, and an electric motor.

19. A vapor-compression evaporation system, comprising:

a plurality of vessels in series each containing a feed having a nonvolatile component;

a steam jet ejector coupled to the first vessel in the series and operable to receive a vapor from the first vessel in the series;

a plurality of heat exchangers coupled inside respective ones of the vessels, the heat exchanger in the first vessel in the series operable to receive the vapor from the steam jet ejector, at least some of the vapor condensing therein, whereby the heat of condensation provides the heat of evaporation to the first vessel in the series; and

wherein at least some of the vapor inside the first vessel in the series is delivered to the heat exchanger in the next vessel in the series, whereby the condensing, evaporating, and delivering steps continue until the last vessel in the series is reached.

20. The vapor-compression evaporation system of claim **19**, wherein the nonvolatile component is selected from the group consisting of salt and sugar.

21. The vapor-compression evaporation system of claim **19**, further comprising a condenser coupled to the last vessel in the series for removing energy from the last vessel in the series.

22. The vapor-compression evaporation system of claim **19**, further comprising a vacuum pump coupled to each of the vessels in the series for removing noncondensibles from the vessels.

23. The vapor-compression evaporation system of claim **19**, further comprising a plurality of devices coupled to respective ones of the vessels for removing concentrated feed from respective ones of the vessels.

24. The vapor-compression evaporation system of claim **19**, further comprising a plurality of sensible heat exchangers coupled to respective ones of the vessels for at least heating the feed before entering respective ones of the vessels.

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