

Title

MULTI-ELEMENT FILTRATION VESSEL

Field of the Invention

5 This invention relates to multi-element filtration vessels.

Background of the Invention

Multi-element filtration vessels are used widely in water treatment facilities to purify water. Semi-permeable membranes are assembled within elements, which
10 are mounted vertically in an array within the vessel. A feed fluid is fed through the elements, where it is separated by the membranes into a concentrate and a permeate. A mixing gas is usually introduced into the vessel at a point below the elements. The mixing gas can perform several useful functions. When the membrane is a hollow fiber type, gas bubbles provide buoyancy, assisting with the transfer of the feed fluid
15 between fibers or through the capillaries in the fibers. The mixing gas also can perform a cleaning function, and improve fluid mixing.

The filtration elements generally include a cylindrical housing which contains the membrane(s). A header is fitted onto one end of the cylindrical housing. The header is an annular piece that fits over the cylindrical housing. Its outside cross-
20 sectional dimensions are larger than the outside dimensions of the cylindrical housing. The larger diameter means that fewer filtration elements can be packed within a pressure vessel of a given size. Increasing the number of filtration elements within a vessel increases its capacity. For large installations, this can mean that fewer filtration vessels are required and/or that the cost of vessels may be spread over a
25 larger number of filtration elements. This would greatly reduce both equipment and operating costs. An improved ratio of filtration element area to vessel cost may also be obtained through more efficient packing. For instance, the existence of edge effects within a vessel of filtration elements can enable non-regular packing geometries to exceed the efficiency of close-packed geometries.

30 Filtration elements are typically cylindrical in shape, and the headers used with them are also generally cylindrical. Making the walls of the headers thinner can reduce the overall cross-section of the filtration element, but in doing so the header can be weakened to the point that it can no longer tolerate the physical stresses

incurred during handling, transportation and use. Thus, the header walls tend to be rather thick, thereby increasing the cross-sectional dimensions of the filtration elements and limiting how tightly the elements can be packed within the pressure vessel.

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Summary of the Invention

This invention addresses that problem by providing a filtration element comprising

10 a) a cylindrical housing having an exterior diameter, the cylindrical housing enclosing an interior portion of the filtration element, the cylindrical housing having opposing first and second ends;

b) at least one filtration membrane disposed within the interior portion of the filtration element;

15 c) one or more openings for admitting a feed fluid through at least one of the opposing first and second ends of the cylindrical housing and into the interior portion of the filtration element;

d) an annular header including a surrounding section that surrounds one of the opposing ends of the cylindrical housing, the surrounding section having a periodically varying cross-sectional width and thickness such that the surrounding section of the annular header has alternating thinner and thicker regions, and

20 e) separate openings for removing permeate and concentrate from the filtration element.

Because of the periodically varying cross-sectional width, the surrounding section of the annular header has alternating thinner regions and thicker regions, the thinner regions being spaced periodically (and preferably regularly) around the circumference of the surrounding section of the annular header. The thinner regions can be made quite small, such as 1-3 mm or less in thickness, because mechanical strength is provided by the alternating thicker regions. When packed into a multi-element filtration apparatus, thinner regions of the annular headers are aligned, allowing adjacent filtration elements to be packed more closely together.

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The invention is also a multi-element filtration apparatus, the apparatus comprising

a) a pressure vessel having a cylindrical shell;

b) multiple filtration elements of the invention arranged vertically inside the cylindrical shell of the pressure vessel, wherein adjacent filtration elements are aligned along thinner regions of the sections of the annular headers surrounding the respective permeate ends of the cylindrical housings of the adjacent filtration
5 elements;

a feed inlet port for introducing a feed fluid into the pressure vessel; a permeate discharge port for discharging from the pressure vessel a permeate produced by the multiple filtration elements, and a concentrate discharge port for discharging from the pressure vessel a concentrate produced by the multiple filtration elements.

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Brief Description of the Drawings

FIGURE 1 is a front view, in section, of a first embodiment of a multi-element filtration apparatus of the invention.

FIGURE 2 is a front view, partially in section, of a filtration element of the
15 invention.

FIGURE 3 is an isometric view of one end of a filtration element of the invention with attached end cap.

FIGURE 4 is an isometric view of an annular header for use in the invention.

FIGURE 5 is an isometric sectional view of an annular header for use in the
20 invention.

FIGURE 5A is an isometric sectional view of a top section of a filtration element of the invention.

FIGURE 6 is a top sectional view of an annular header for use in the invention.

FIGURE 7 is a side view of an annular header for use in the invention.

FIGURE 7A is a rotated view of the annular header shown in Figure 7.
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FIGURE 8 is a top view of an arrangement of filtration elements of the invention.

FIGURE 9 is a top view of a module pack within a pressure vessel with support plate.

FIGURE 10 is a front view, in section, of a second embodiment of a filtration
30 apparatus of the invention.

Detailed Description of the Invention

Turning to Figure 1, multi-element filtration apparatus **15** includes pressure vessel **1**, which in the embodiment shown includes shell **2** and removable lid **9**. Preferably, shell **2** is cylindrical and pressure vessel **1** is suitable for operation with inside pressures exceeding at least two bars above the outside pressure. A filtration chamber **16** is surrounded by the shell **2** and pressure plate **18**. Filtration elements **3** are disposed vertically within filtration chamber **16**. In this embodiment filtration elements **3** are aligned and supported by at least one of pressure plate **18**, support plate **13** and bottom support plate **12**. Support plate **13** as shown includes openings for receiving filtration elements **3** such that headers **22** rest on support plate **13**.

In the embodiment shown in Figure 1, feed fluid to be treated is introduced under pressure into multi-element filtration apparatus **15** through inlet port **4**, where it passes through openings in bottom support plate **12** and enters filtration elements **3** through holes **27** in first ends **24** of filtration elements **3** (see Figure 2). Filtration elements **3** contain one or more membranes **26** (Figure 2), which allow a portion of the feed fluid to pass through, thereby producing permeate (or filtrate) and a concentrate (or reject) stream containing a small portion of the feed fluid plus materials that do not pass through the pores of the membrane.

In the embodiment shown in Figures 1, 3 and 4, concentrate is withdrawn from filtration elements **3** through openings **33** in annular header **22** and withdrawn from pressure vessel **1** through concentrate port **6**. In alternative embodiments, instead of or in addition to openings **33**, openings for withdrawing concentrate from filtration elements **3** may be present within the cylindrical housing **21**. In either case, permeate passes through central opening **35** of annular header **22** into collection chamber **10** of pressure vessel **1**, from which it is removed via permeate port **5**. In the particular embodiment shown, optional end cap **23** is mounted onto annular header **22** and forms a conduit for permeate exiting central opening **35** into collection chamber **10**, permeate flowing into collection chamber **10** through outlet **34** of end cap **23**. As shown, end cap **23** extends through pressure plate **18**. Alternatively, annular header **22** may be in direct fluid communication with collection chamber **10** through openings in pressure plate **18**. Collection chamber **10** during operation usually is maintained at a lower pressure than filtration chamber **16**. Filtration element **3** and pressure

vessel **1** can alternatively be designed such that concentrate passes through outlets **34** and permeate is removed via port **6**. This can be done, for example, by operating in an inside-out mode of operation with both top and bottom ends of the hollow fiber membranes being open.

5 Optional aerator **11** provides a mixing gas that is introduced into first ends **24** of filtration elements **3**. Introducing both gas and feed fluid from the bottom end of the filtration element **3** can induce an upward force on feed fluid to drive concentrate towards openings **33**. Openings **33** for concentrate may be in the cylindrical housing **21** or the header **22**, but these openings **33** are separated from the permeate outlet **34**
10 by a seal, such a layer of potting **31**, as shown in Figure 5.

 Although the embodiment shown in Figure 1 is designed to operate with feed fluid being introduced from the bottom and concentrate and permeate being removed from the top, in alternative embodiments multi-element filtration apparatus **15** can be configured to operate with feed fluid being introduced into the top and concentrate
15 being withdrawn from the bottom. Additionally, the embodiment shown in Figure 1 can alternatively be designed with openings in support plate **13** that allow concentrate to drain into filtration chamber **16**, from which it can be removed through an appropriate port.

 Turning to Figure 2, filtration element **3** includes cylindrical housing **21**, which
20 encloses an interior space, in which one or more filtration membranes **26** are disposed. Filtration element **3** has opposing first and second ends **24** and **25** at opposing ends of cylindrical housing **21**. During normal operation a feed fluid is introduced into first end **24** through inlet holes **27**, and permeate and concentrate flow out of second end **25** into annular header **22**. In the embodiment shown in Figure 2, inlet holes **27** pass
25 through the lower end of a potting layer **31'**. Inlet holes **27** may alternatively pass through optional collar **29** or through a location on the cylindrical housing **21**, below potting layer **31'**. Optional collar **29** may cover first end **24**. Optional end cap **23** is mounted on annular header **22**; in the particular embodiment shown, end cap **23** is in fluid communication with annular header **22** and collection chamber **10** of pressure
30 vessel **1**, to allow permeate to flow out of filtration element **3** and, in the embodiment shown Figure 1, into collection chamber **10**.

Annular header **22** is in the general shape of a ring with a central opening **35**. That portion of central opening **35** that surrounds cylindrical housing **21** is generally circular to correspond to the exterior shape of cylindrical housing **21**.

Annular header **22** includes a surrounding section **30** that surrounds an end
5 (as shown, second end **25**) of cylindrical housing **21**. Surrounding section **30** has a periodically varying cross-sectional width, as shown in more detail in Figure 6. Starting at any arbitrary point A on the outer surface of surrounding section **30** of annular header **22**, the cross-sectional width of surrounding section **30** changes in a periodic manner around the circumference of surrounding section **30**. Thus, in Figure
10 6, surrounding section **30** has a cross-sectional width $W_{\max}$ at point A. Moving clockwise around surrounding section **30** as shown in Figure 6, the cross-sectional width first decreases, reaching $W_{\min} < W_{\max}$ at point B, then increases to again attain $W_{\max}$ at point C, and thereafter periodically decreases and increases between $W_{\min}$ and $W_{\max}$ until one returns to starting point A. This produces alternating thinner regions
15 **52** and thicker regions **53**, reaching relative minima at points such as point B, where the width decreases to $W_{\min}$. Thinner regions **52** are spaced periodically (and preferably regularly) around the circumference of section **30** of annular header **22**. The periodic variation in the thickness of surrounding section **30** produces relative minima, which preferably appear at repeating intervals of 30 to 120 degrees, and most
20 preferably at repeating intervals of 60 degrees.

Thinner sections **52** may have thicknesses, at the thinnest point, in the range of, for example 0.5 to 3 mm. Thicker sections **53**, at their thickest point, may have thicknesses, for example, 1.4 to 5 times the minimum thickness of thinner sections **52**, such as, for example, from 1 to 15 mm, especially 2 to 8 mm.

25 In the particular embodiment shown in Figures 3-7A, surrounding section **30** of annular header **22** has a preferred generally regular hexagonal outside cross-sectional shape. Vertices **50** may be rounded or beveled, if desired, rather than forming sharp points as shown in Figures 3-7A. Sides **51** of surrounding section **30** preferably are flat as shown in Figure 5. Alternatively, surrounding section **30** may
30 have any arbitrary number of sides, ranging from as few as three (it being generally triangular in cross-section in that case), four, or five, or as many as, for example, 12, 10 or 8 sides.

At all points about the circumference of filtration element **3**, surrounding section **30** preferably has the largest cross-sectional width of any component of filtration element **3**. Especially at points about the circumference of the filtration element **3** corresponding to regularly-spaced relative minima in the surrounding section **30**, $W_{\min}$ is preferably equal to or greater than the cross sectional width of each of the cylindrical housing **21**, any optional collar **29**, and any end cap **23**. Referring to Figures 7 and 7A, the minimum width $W_{\min}$ of surrounding section **30** of annular header **22** is equal to or greater than the cross-sectional width D of cylindrical housing **21**, and the maximum width $W_{\max}$ of surrounding section **30** is greater than cross-sectional width D . End cap **23** as well as any collar **29** or other components as may be present, have a minimum width that is less than or equal to $W_{\min}$ and a maximum width that is preferably no greater than $W_{\min}$. Preferably, at any point about the circumference of filtration element **3**, any collar **29** and end cap **23** have a cross-sectional width equal to or less than that of the corresponding (at the same radial position) surrounding section **30** of annular header **22** at that point. Collar **29**, when present, may have a periodically varying cross-sectional width as described with regard to surrounding section **30** of annular header **22**.

Each membrane **26** may be, for example, a microfiltration membrane, ultrafiltration membrane, a nanofiltration membrane or a reverse osmosis membrane. Most preferred is an ultrafiltration membrane. In a preferred embodiment, the membranes take the form of hollow fiber membranes, but they can be spiral wound or have other configurations if desired.

The preferred hollow fiber membranes are potted within filtration element **3**, typically at both opposing ends (**24**, **25**) of filtration element **3**. The capillary openings of hollow fiber membranes are open on at least one end of the filtration element **3**. In certain embodiments adapted for an outside-to-inside mode of permeating operation, capillary openings may be open on both ends, but they are preferably closed off at one end. Capillaries may be blocked at the first end **24**, such as by being buried within the potting, and capillaries may be open and extend through the potting at the opposing second end **25** to allow permeate to exit the element. Referring to the configuration illustrated in Figure 2, a potting layer **31'** seals the capillaries of hollow fiber membranes **26**, but the potting layer **31'** also contains inlet holes **27** that pass

through the potting layer **31'** and allow feed fluid to enter the filtration element **3**. In other configurations (e.g., Fig. 10), capillary openings may be closed off at the second end **25**, with open capillaries extending through the potting at the first end **24**.

Permeate and concentrate are removed from the filtration element **3** at separate openings. In preferred embodiments with outside-to-inside permeation through hollow fibers, the permeate is removed from open capillaries of hollow fibers at either the top or bottom of the filtration element **3**. In filtration elements adapted for inside-to-outside permeation, the capillary openings are generally open through pottings on both ends of the filtration element, allowing permeate to be removed from openings such as openings **33** of annular header **22**, or other openings in cylindrical housing **21**.

In the embodiments shown in Figures 5 and 5A, hollow fiber membranes **26** are potted at one end within header **22**. In this particular embodiment, header **22** includes optional annular extension **32** that extends past second end **25** of cylindrical housing **21**. As shown, membranes **26** may be sealed within a potting layer **31** that is located within annular extension **32**, extending through potting layer **31** and being in fluid communication with collection chamber **10** via optional end cap **23**. In the embodiment shown in Figure 5, openings **33** are provided in annular header **22**, between potting layer **31** and second end **25** of cylindrical housing **21**, for removing concentrate (in the preferred outside-in mode of operation) or permeate (in the less preferred inside-out configuration). In the embodiment shown in Figure 5A, openings **33** for removing permeate or concentrate from the filtration element instead are provided through cylindrical housing **21**.

In some embodiments, hollow fiber membranes **26** are potted within surrounding section **30** of annular header **22**, and/or within cylindrical housing **21**, with appropriately located openings below the potting for removing concentrate or permeate, as the case may be.

Annular header **22** may include annular extension **32** even in cases in which membranes **26** do not extend into annular header **22** or past surrounding section **30** of annular header **22**. For example, annular extension **32** may serve as a mounting region for optional end cap **23**.

At locations radially aligned with thin regions (corresponding to relative minimums in thickness of the surrounding section **30**), the annular extension **32** preferably has a cross-sectional width that is no greater than the minimum width $W_{\min}$ of surrounding section **30** of annular header **22**. Preferably, annular extension **32** has a smaller cross-sectional width, at all points around the circumference of filtration element **3**, than that of surrounding section **30** of annular header **22**. Annular extension **32** preferably has a circular outer perimeter having a diameter less than or equal to the minimum cross-sectional width of surrounding section **30** of annular header **22**. Similarly, any end cap **23** preferably has a cross-sectional width, at all points around the circumference of filtration element **3**, equal to or less than that of surrounding section **30** of annular header **22**.

Optional end cap **23** is hollow and preferably includes at least one outlet **34** which is in fluid communication with both annular header **22** and collection chamber **10**, thereby forming a fluid passageway between them.

End cap **23** preferably is removably mounted onto annular header **22**, as this allows end cap **23** to be removed from annular header **22** to, for example, perform cleaning and/or maintenance (*e.g.*, sealing of broken fibers). In the embodiment shown, annular extension **32** of annular header **22** includes threading **36** on its exterior surface. In such a case, reciprocal threading is provided on the mating interior surface of end cap **23**. In another embodiment, annular extension **32** includes threading **36** on its interior surface and reciprocal threading is provided on the mating exterior surface of the end cap **23**. Other mounting apparatus may be provided instead of or in addition to threading, such as groove and ridge mounts, various types of snap mounts, and the like.

Multiple filtration elements **3** of the invention are arranged vertically inside shell **2** of pressure vessel **1** to form a module pack. A module pack may contain, for example, 2 to 150 or more filtration elements **3**, with 55 to 131 being an especially useful number of elements for many applications. In other preferred embodiments, the number of filtration elements **3** within a module pack may be selected from 55, 61, 73, 85, 91, 97, 119, or 131.

Figures 8 and 9 illustrate a suitable packing mode using preferred filtration elements **3** that have a cylindrical housing **21** and header **22** in which surrounding

section 30 has the shape of a regular hexagon. As shown in Figure 8, adjacent filtration elements 3 are aligned along one side of surrounding sections 30 of their respective annular headers 22. The aligned sides of the respective surrounding sections 30 of annular headers 22 are thinner regions 52 of the respective headers. Thicker regions 53 reside within gaps 60 formed where two or more filtration elements 3 come together. This allows close packing of filtration elements 3, as packing density is determined by the width $W_{\min}$ of surrounding section 30 of annular header 22. Thicker sections 53 provide mechanical strength to annular header 22. Note that a conventional header of circular cross-section, having a constant width and thickness, will typically need to be thicker than thinner section 52 to provide the requisite mechanical properties. This increased thickness increases the spacing between elements and reduces the number of elements that can be packed within a given volume.

Module packs comprising filtration elements of the invention typically have an irregular outer periphery, as shown in Figure 9. In some embodiments, support plate 13 occupies some or all of the space between the irregular outer periphery of the module pack and shell 2, or otherwise provides flow resistance between the irregular outer periphery of the module pack and shell 2. Support plate 13 may form a complete barrier to fluid flowing from above to below support plate 13, or may be a partial barrier having openings that allow fluid to flow from above to below support plate only at specified locations and/or at specified rates. Support plate 13 or any portion thereof may be canted or otherwise adapted to promote fluid flow in a particular direction or directions, such as toward a concentrate port such as concentrate port 6 in Figure 1. In another embodiment, support plate 13 occupies some or all of the space between the irregular outer periphery of the module pack and shell 2.

Figure 8 illustrates another optional but preferred feature, *i.e.*, locking means for locking adjacent filtration elements together. In the particular embodiment shown, the locking means includes clips 41 and receiving notches 40, which are adapted to receive and hold clips 41. Other mechanical locking means include a variety of latches and/or clips. Magnetic locking means are also useful. The locking means preferably is adapted to be opened and re-closed to allow easy removal or unpacking of filtration elements from the module pack.

Multi-element filtration apparatus **15** may further include various auxiliary apparatus such as pumps, valves, seals, instrumentation, piping, ductwork and the like as may be desirable or useful.

5 The multi-element filtration apparatus of the invention is in general operable in the same way as conventional multi-element filtration apparatus. Flow of feed fluid within a filtration element **3** may be driven, up or down, based on an induced pressure differences. During operation of a pressure vessel as shown in Figure 1, for example, a feed fluid may be introduced into pressure vessel **1** of multi-element filtration apparatus **15** via feed inlet port **4**, and this alone could create an upward flow of feed fluid within the filtration element **3** if there were sufficient resistance to flow of feed fluid around the filtration elements **3**. Such resistance may be provided, for instance, by the tight positioning of adjacent modules with annular headers. Alternatively, an upward movement of feed fluid within filtration elements **3** may be created by air bubbles. Referring again to Figure 1, mixing gas is supplied into filtration element **3** by aerator **11**, and the bubbles used to keep membranes **26** clean can also create an upward flow of feed fluid within the filtration element **3**. Creation of an upward feed fluid flow within the filtration elements **3** is desired during operation, but it is also possible to create a downward flow of feed fluid by reversing the position of inlet port **4** and outlet port **6**.

20 Upon entering interior portions of filtration elements **3**, mixing gas and feed fluid travel upward through filtration elements **3**, coming into contact with the filtration membranes **26**, which separate the feed fluid into a permeate that passes through the membrane and a concentrate or reject that includes one or more concentrated materials that are rejected by the membrane and are thus prevented from passing through it. The permeate and concentrate are taken separately from at or near second ends **25** of filtration elements **3**. In the preferred manner of operating the multi-element filtration apparatus **15** of Figure 1, for example, permeate is removed from pressure vessel **1** via permeate port **5**. Concentrate is removed from pressure vessel **1** via concentrate port **6**. Mixing gas can be vented through concentrate port **6** or a separate air vent (not shown).

30 In the case of hollow fiber membranes operated with permeation in an outside-to-inside manner, the mixing gas and feed fluid are supplied to and contacted with the

exterior surfaces of the hollow fiber membranes **26**. A portion of the fluid passes through the hollow fiber membranes **26** and into their respective capillaries to produce the permeate, the concentrate in that case being that portion of the feed fluid and rejected materials that do not pass through and into the hollow fibers. The apparatus
5 of the invention can also be operated in an inside-out manner, with feed fluid being fed into the capillaries.

In other embodiments, multi-element filtration apparatus **15** is designed for and operated with top-to-bottom flow of feed fluid, with feed fluid being introduced above filtration elements **3** and concentrate and permeate being removed from the
10 bottom of filtration elements **3**. The direction of feed fluid flow may be selected independent of whether permeate is removed from the top or bottom of a filtration element **3**.

In Figure 10, an alternate embodiment of multi-element filtration apparatus **115** includes pressure vessel **101**, which in the embodiment shown includes shell **102**
15 and removable lid **109**. Preferably, shell **102** is cylindrical and pressure vessel **101** is suitable for operation with inside pressures exceeding at least two bars above the outside pressure. A filtration chamber **116** is surrounded by the shell **102** and pressure plate **118**. Filtration elements **103** are disposed vertically within filtration chamber **116**. In this embodiment filtration elements **103** are aligned by at least one
20 of positioner **108** and support plate **113**. Positioner **108** may provide alignment, mechanical support and/or function a flow restrictor to maintain pressure drops necessary for operation. Support plate **113** as shown includes openings for receiving filtration elements **103** such that headers **122** rest on support plate **113**. In this embodiment, filtration elements are inverted compared to the Figure 1 embodiment,
25 with headers **122** at the bottoms of the elements as installed.

In operation, feed fluid enters pressure vessel **101** via feed inlet **104** and enters filtration elements **122** via openings **133**. As before, optional aerator **111** supplies gas bubbles that enter openings **133** together with feed fluid to provide buoyancy. The capillaries of hollow fiber membranes in this particular embodiment are open at the
30 bottom of filtration elements **103** and closed at the top. In an outside-to-inside mode of operation, a portion of feed fluid entering openings **133** passes through pores in the hollow fibers to produce permeate within the capillaries. With the geometry of Figure

10, the permeate flows downward, through the header **122** and optional end cap **123** into collection chamber **110** and then out via permeate port **105**. As before, pressure plate **118** separates filtration chamber **116** from collection chamber **110**, which is at a lower pressure than filtration chamber **116**. Concentrate is removed from the top end
5 of filtration elements **103** via holes **150**. In the particular embodiment shown, concentrate exiting holes **150** enters filtration chamber **116** and is removed from pressure vessel **101** via concentrate port **106**.

The multi-element filtration apparatus of the invention is useful for filtering a wide variety of fluids, especially aqueous fluids such as groundwater, surface water,
10 seawater, process streams from chemical operations and/or power generating stations, as well as many others. In a particular embodiment, the multi-element filtration apparatus is a seawater ultrafiltration and/or microfiltration apparatus, and can be used, for example, as a prefilter for preparing seawater for reverse osmosis to produce potable water.

15 Although the present invention has been described in terms of specific exemplary embodiments, it will be appreciated that various modifications and alterations might be made by those skilled in the art without departing from the spirit and scope of the invention as set forth in the following claims.

Claims

What is claimed is:

1. A filtration element comprising
 - a) a cylindrical housing having an exterior diameter, the cylindrical housing enclosing an interior portion of the filtration element, the cylindrical housing having opposing first and second ends;
 - b) at least one filtration membrane disposed within the interior portion of the filtration element;
 - c) one or more openings for admitting a feed fluid through at least one of the opposing first and second ends of the cylindrical housing and into the interior portion of the filtration element;
 - d) an annular header including a surrounding section that surrounds one of the opposing ends of the cylindrical housing, the surrounding section having a periodically varying cross-sectional width and thickness such that the surrounding section of the annular header has alternating thinner and thicker regions, and
 - e) separate openings for removing permeate and concentrate from the filtration element.
2. The filtration element of claim 1 wherein the thickness of the surrounding section of the annular header periodically varies to produce relative minima at regular intervals of 30 to 120 degrees.
3. The filtration element of claim 2 wherein the thickness of the surrounding section of the annular header varies periodically to produce relative minima at repeating intervals of 60 degrees.
4. The filtration element of any of claims 1-3 wherein the section of the annular header surrounding the outlet of the cylindrical housing has six flat exterior faces arranged regularly about the circumference of the section with vertices between each pair of adjacent flat exterior faces, the vertices optionally being curved or beveled.

5. The filtration element of claim 4 wherein the section of the annular header surrounding the outlet of the cylindrical housing has a regular hexagonal cross-section.

6. The filtration element of any preceding claim wherein the at least one filtration membrane extends into the annular header and is potted within the annular header.

7. The filtration element of claim 6 wherein the at least one filtration membrane extends through the potting and is in fluid communication with a fluid collection region external to both the cylindrical housing and the annular header for receiving permeate.

8. The filtration element of claim 7 wherein the annular header further comprises an annular extension that extends past the surrounded end of the cylindrical housing, the at least one filtration membrane is potted within the annular extension, and the annular header has openings between the potting and the end of the cylindrical housing for removing concentrate from the annular header.

9. The filtration element of claim 8 wherein the annular extension has a circular outer perimeter having a diameter less than or equal to the minimum cross-sectional width of the surrounding section of the annular header.

10. The filtration element of claim 8 or 9 further comprising an end cap affixed to and in fluid communication with both the annular header and the fluid collection region.

11. The filtration element of claim 10 wherein the end cap is removably affixed to the annular extension of the annular header.

12. A multi-element filtration apparatus, the apparatus comprising
a) a pressure vessel having a shell;

b) multiple filtration elements of any of claims 1-11 arranged vertically inside the shell of the pressure vessel, wherein adjacent filtration elements are aligned along thinner regions of the surrounding sections of the annular headers of the adjacent filtration elements;

a feed inlet port for introducing a feed fluid into the pressure vessel; a permeate discharge port for discharging from the pressure vessel a permeate produced by the multiple filtration elements, and a concentrate discharge port for discharging from the pressure vessel a concentrate produced by the multiple filtration elements.

13. The multi-element filtration apparatus of claim 12 wherein the multiple filtration elements are removably mounted on the support.

14. The multi-element filtration apparatus of claim 13 wherein the support comprises a support plate within the pressure vessel, the support plate having openings for receiving filtration elements, and the annular headers rest on and are supported by the support plate.

15. The multi-element filtration apparatus of any of claims 12-14 further comprising one or more aerators for supplying a mixing gas to the multiple filtration elements.

16. The multi-element filtration apparatus of any of claims 12-15 wherein the concentrate discharge port is located above the annular headers of the filtration elements.

17. The multi-element filtration apparatus of any of claims 12-16 wherein the multiple filtration elements form a module pack having an irregular outer periphery.

18. The multi-element apparatus of claim 17 wherein the annular headers rest on and are supported by a support plate, and the support plate provides flow resistance between the irregular outer periphery of the module pack and the shell.

19. The multi-element filtration apparatus of any of claims 12-18 further comprising locking means for locking adjacent filtration elements together.