

BRAIDED HOLLOW FIBER MEMBRANE COMPOSITE STRUCTURES

Field of Invention

- 5 The present disclosure generally relates to membrane composite structures, and more particularly relates to braided hollow fibre membrane composite structures.

Background

- 10 The listing or discussion of a prior-published document in this specification should not necessarily be taken as an acknowledgement that the document is part of the state of the art or is common general knowledge.

Membrane technology has been becoming increasingly prevalent as a reliable and effective
15 treatment process to treat polluted water and generate clean water. Compared with other water treatment approaches, membrane technology is extensively adopted owing to its many advantages such as lesser use of chemicals, lower footprint, and high quality of produced water. Among the different types of membranes, the hollow fibre membrane (HFM) is especially attractive due to its high packing density and facile operations. Compared to the
20 traditional plate and spiral wound modules which possess surface area/volume ratio of 350~500 and 650~800 m²/m³, respectively, the value for HFM can reach 7000~13000 m²/m³, enabling higher treatment throughput for an equivalent footprint.

HFM has been widely used in water purification and other liquid separation processes, by
25 using the process of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), etc. However, despite its increasing applications, the as-prepared HFMs from phase separation methods suffer from low mechanical performance, with tensile strength basically equal to or less than 5 MPa. In addition, it is easy for HFM to get contaminated, which consequently will result in significant reduction in membrane performance, such as reduced filtration flux. As such, the
30 long-term operation of HFM requires the use of mechanical cleaning regimes, which include the use of backwash, vigorous aeration as well as air scouring in membrane tanks or modules, to effectively get rid of the contamination and recover the membrane performance. Aeration creates shear force on the surface of the membranes and cause physical movement of the fibres. Such movement effects are created to allow the deposits on the membrane surfaces to
35 detach and reduce fouling tendencies after long operation periods. Nonetheless, poor mechanical properties can cause HFM to be vulnerable and damaged during the high-pressure water flow and turbulence or high-speed aeration, during operation and cleaning.

Hence, for optimal performance, appropriate mechanical properties of HFMs are necessary to withstand the movement during operation/cleaning without damage.

Until now, commonly used methods to reinforce HFM include porous matrix reinforcement, filaments/threads incorporation and using braiding structure. These methods were proven to be able to effectively enhance the mechanical properties of HFM. Generally, the porous matrix reinforcement and filament/threads incorporation methods can lift the tensile strength of HFM to 10~25 MPa and 10~100 MPa, respectively, while the use of the embedded braiding structure can increase the strength up to as high as 170 MPa. However, there are limitations and drawbacks arising from the introduction of external reinforcement elements. For example, the homogeneous porous matrix reinforcement could be partially dissolved by casting solutions, while the process of heterogeneous reinforcement is usually costly in addition to interfacial issues. Furthermore, the porous matrix reinforcement can only contribute limited mechanical enhancement. For filament/thread incorporation, new failure modes can be introduced due to thermophysical incompatibilities between the filler and polymer matrix. Different braiding materials and methods have been previously disclosed but the manufacturing process of homogenous or heterogeneous braids can be costly and there are significant challenges in obtaining uniform coating onto the braiding structure to obtain consistent thickness. Overall, these approaches make the HFM fabrication process complex and add inconsistency in final products.

Therefore, to overcome at least one of the aforementioned problems, there exists a need for new braided hollow fibre membrane composite structures and methods of forming braided hollow fibre membrane composite structures.

Summary of Invention

Herein, a new type of braided hollow fibre membrane composite structures and methods of forming braided hollow fibre membrane composite structures is provided to effectively enhance the mechanical properties of hollow fibre membrane.

Aspects and embodiments of the invention are provided in the following numbered clauses.

1. A braided hollow fibre membrane composite structure, comprising:
one or more hollow fibre membranes; and
one or more reinforcing fibres, wherein

the one or more hollow fibre membranes are co-braided with the one or more reinforcing fibres, wherein the force to fracture a single hollow fibre membrane in the braided hollow fibre membrane composite structure is greater than the force to fracture a single hollow fibre membrane that is not braided.

5

2. The braided hollow fibre membrane composite structure according to Clause 1, wherein the force to fracture the single hollow fibre membrane in the braided composite structure has a value that is at least 150% greater than the force to fracture a single hollow fibre membrane that is not braided, such as a value that is at least 200% greater.

10

3. The braided hollow fibre membrane composite structure according to Clause 1 or Clause 2, wherein a total number of fibres obtained by the addition of a total number of the one or more hollow fibre membranes and a total number of the one or more reinforcing fibres is from 2 to 100, provided that there is at least one hollow fibre membrane and at least one

15

4. The braided hollow fibre membrane composite structure according to Clause 3, wherein the total number of the one or more hollow fibre membranes is from 1 to 99, such as from 2 to 6.

20

5. The braided hollow fibre membrane composite structure according to Clause 3, wherein the total number of the one or more reinforcing fibres is from 1 to 99, such as from 1 to 3.

25

6. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein each of the one or more hollow fibre membranes is independently formed from an organic polymeric material that is capable of forming a hollow fibre membrane that can be used to separate at least two materials from one another in a fluid.

30

7. The braided hollow fibre membrane composite structure according to Clause 6, wherein each of the one or more hollow fibre membranes is independently formed from an organic polymeric material selected from one or more of the group consisting of PSF (polysulfone), PES (polyethersulfone), PC (polycarbonate), PEI (poly (ether imide)), PTFE (polytetrafluoroethylene), PAN (polyacrylonitrile), cellulose, cellulose derivatives and, more particularly, polyvinylidene fluoride, polypropylene, and polyethylene.

35

8. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein each of the one or more hollow fibre membranes is independently a symmetric hollow fibre membrane or an asymmetric hollow fibre membrane, optionally wherein all of the hollow fibre membranes in the braided hollow fibre membrane composite structure are all symmetric or are all asymmetric.
9. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein each of the one or more reinforcing fibres is independently in the form of a wire, a filament, a strand, and a yarn.
10. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein each of the one or more reinforcing fibres is independently formed from an organic polymeric material, an inorganic material or a combination thereof.
11. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein each of the one or more reinforcing fibres is solid or hollow.
12. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein each of the one or more reinforcing fibres is independently selected from one or more of the group consisting of a PSF (polysulfone), PES (polyethersulfone), PC (polycarbonate), PEI (poly (ether imide)), PTFE (polytetrafluoroethylene), PAN (polyacrylonitrile), cellulose, cellulose derivatives, and, more particularly, metal (e.g. stainless steel), polypropylene, polyethylene, polyvinylidene fluoride, nylon, polyethylene terephthalate, and carbon fibres.
13. The braided hollow fibre membrane composite structure according to Clause 12, wherein one or more of the following apply:
- (aa) when the one of the one or more reinforcing fibres are formed from a same material as at least one of the one or more hollow fibre membranes, then it is also a hollow fibre membrane with identical properties; and
- (bb) when at least one of the one or more reinforcing fibres are formed from a same material as at least one of the one or more hollow fibre membranes, then it differs from the same material in the one or more hollow fibre membranes in one or more of its thermal transition behaviour (e.g. one or more of glass transition temperature, melting temperature, and melt flow index), mechanical performance (e.g. strength, modulus and breakage strain), molecular weight, molecular weight distribution, and density.

14. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein a braiding angle obtained at any point of the composite structure has a value of from greater than 0 to less than 90°, such as from 10 to 60°, where the braiding angle is measured as a fibre angle relative to a longitudinal direction of the braided composite structure.
15. The braided hollow fibre membrane composite structure according to Clause 14, wherein an average braiding angle is from 10 to 30° based on the average value of 10 braiding angle measurements, such as 12.6°.
16. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein a maximum deflection of the braided hollow fibre membrane composite structure accounts for from 0% to 80% of the length of the braided hollow fibre membrane composite structure, such as from 10% to 53%, such as from 20% to 61%.
17. The braided hollow fibre membrane composite structure according to any one of the preceding clauses, wherein the braided hollow fibre membrane composite structure is selected from the list
- (a) two or more polypropylene hollow fibre membranes;
 - (b) two or more polyethylene hollow fibre membranes;
 - (c) two or more PVDF hollow fibre membranes; and, more particularly,
 - (d) one or more PVDF hollow fibre membranes and one or more PVDF reinforcing fibres;
 - (e) one or more PP hollow fibre membranes and one or more PP reinforcing fibres;
 - (f) one or more PE hollow fibre membranes and one or more PE reinforcing fibres;
 - (g) one or more PP hollow fibre membranes and one or more PE reinforcing fibres;
 - (h) one or more PE hollow fibre membranes and one or more nylon reinforcing fibres;
 - (i) one or more PVDF hollow fibre membranes and one or more PET reinforcing fibres;
 - (j) one or more PP hollow fibre membranes and one or more metal wire reinforcing fibres;
 - (k) one or more PVDF hollow fibre membranes and one or more PE reinforcing fibres;
 - (l) one or more PE hollow fibre membranes and one or more metal wire reinforcing fibres;
 - (m) one or more PP hollow fibre membranes and one or more nylon reinforcing fibres;
 - (n) one or more PE hollow fibre membranes, one or more nylon reinforcing fibres, and one or more strands of carbon fibre reinforcing fibres; and
 - (o) one or more PE hollow fibre membranes, and one or more strands of carbon fibre reinforcing fibres.

18. The braided hollow fibre membrane composite structure according to Clause 17, wherein the braided hollow fibre membrane composite structure is selected from the list:
- (ai) three polypropylene hollow fibre membranes, where at least one of the three polypropylene hollow fibre membranes is a reinforcing fibre;
 - 5 (aii) three PE hollow fibre membranes and one hollow PP reinforcing fibre;
 - (aiii) three PE hollow fibre membranes, one solid PE reinforcing fibre, and one strand of carbon fibre reinforcing fibre; and, more particularly,
 - (aiv) two PE hollow fibre membranes and two PE reinforcing fibres (e.g. two solid PE reinforcing fibres);
 - 10 (av) six PP hollow fibre membranes and one metal wire reinforcing fibre (e.g. one solid metal wire reinforcing fibre);
 - (avi) two PVDF hollow fibre membranes and three PE reinforcing fibres (e.g. three solid PE reinforcing fibres);
 - (avii) two PE hollow fibre membranes and one PE reinforcing fibre (one solid PE reinforcing fibre);
 - 15 (aviii) five PP hollow fibre membranes and two nylon reinforcing fibres (e.g. two solid nylon reinforcing fibres); and
 - (aix) three PE hollow fibre membranes, and one strand of carbon fibre reinforcing fibre.
- 20 19. A method of forming a braided hollow fibre membrane composite structure as described in any one of Clauses 1 to 18, wherein the method comprises:
- (bi) one or more hollow fibre membranes and one or more reinforcing fibres; and
 - (bii) intertwining the one or more hollow fibre membranes with the one or more reinforcing fibres a plurality of times to form the braided hollow fibre membrane composite structure.

25

Drawings

FIG. 1 depicts steps of making a braided composite structure comprising two HFM and one reinforcing fiber.

30

FIG. 2 depicts steps of making a braided composite structure comprising two HFM and two reinforcing fibers.

FIG. 3 depicts steps of making a braided composite structure comprising three HFM and one strand of reinforcing fiber.

35

FIG. 4 depicts steps of making a braided composite structure comprising three HFM braided with two different reinforcing fibers.

FIG. 5 depicts steps of making a braided composite structure comprising five HFM and two reinforcing fibers.

FIG. 6 depicts a setup of the deflection test.

FIG. 7 depicts a braided HFM composite structure comprising two polyethylene (PE) hollow fibre and two solid reinforcing PE fibres.

FIG. 8 depicts the deflection of braided HFM composite structure comprising two PE hollow fibres and two solid reinforcing PE fibres.

FIG. 9 depicts the deflection of four PE HFM.

FIG. 10 depicts the deflection of one PE HFM.

FIG. 11 depicts a braided HFM composite structure comprising six polypropylene (PP) HFM and one solid reinforcing metal wire.

FIG. 12 depicts deflection of a braided HFM composite structure comprising six PP HFM and one solid reinforcing metal wire.

FIG. 13 depicts deflection of six PP HFM.

FIG. 14 depicts a braided HFM composite structure comprising two polyvinylidene fluoride (PVDF) HFM and three solid reinforcing PE fibers.

FIG. 15 depicts deflection test of braided HFM composite structure comprising two PVDF HFM and three solid reinforcing PE fibers.

FIG. 16 depicts deflection test of two PVDF HFM.

FIG. 17 depicts a braided HFM composite structure comprising two PP HFM and one solid reinforcing PE fiber.

FIG. 18 depicts deflection of braided HFM composite structure comprising two PP HFM and one solid reinforcing PE fiber.

FIG. 19 depicts deflection of three PP HFM.

FIG. 20 depicts deflection of one PP HFM.

FIG. 21 depicts a braided HFM composite structure comprising three PP HFM.

FIG. 22 depicts braided HFM composite structure comprising three PE HFM and one hollow reinforcing PP fiber.

FIG. 23 depicts a braided HFM composite structure comprising five PP HFM and two solid reinforcing nylon fibers.

FIG. 24 depicts deflection of braided HFM composite structure comprising five PP HFM and two solid reinforcing nylon fibers.

FIG. 25 depicts deflection of five PP HFM.

FIG. 26 depicts a braided HFM composite structure comprising three PE HFM, one strand of reinforcing carbon fibers and one solid reinforcing PE fiber.

FIG. 27 depicts deflection of braided HFM composite structure comprising three PE HFM, one strand of reinforcing carbon fibers and one solid reinforcing PE fiber.

FIG. 28 depicts a braided HFM composite structure comprising three PE HFM and one strand of reinforcing carbon fibers.

FIG. 29 depicts deflection of braided HFM composite structure comprising three PE HFM and one strand of reinforcing carbon fibers.

FIG. 30 depicts deflection of three PE HFM.

Description

The present invention provides braided hollow fibre membrane (HFM) composite structures which comprise one or more hollow fibre membrane braided with one or more reinforcing fibres. It has been surprisingly found that, contributed by the excellent mechanical properties of the reinforcing fibre and effective load transfer, the force to fracture the HFM could be significantly increased in braided composite structures compared with individual fibres without braiding. The deflection of the braided composite structures under aeration cleaning could be well adjusted by controlling the braiding design. The braided HFM composite structures disclosed herein may be used to minimize HFM damage and maximize flux recovery during cleaning processes.

10

Thus, in a first aspect of the invention, there is provided a braided hollow fibre membrane composite structure, comprising:

one or more hollow fibre membranes; and

one or more reinforcing fibres, wherein

15

the one or more hollow fibre membranes are co-braided with the one or more reinforcing fibres, wherein the force to fracture a single hollow fibre membrane in the braided hollow fibre membrane composite structure is greater than the force to fracture a single hollow fibre membrane that is not braided.

20

In embodiments herein, the word "comprising" may be interpreted as requiring the features mentioned, but not limiting the presence of other features. Alternatively, the word "comprising" may also relate to the situation where only the components/features listed are intended to be present (e.g. the word "comprising" may be replaced by the phrases "consists of" or "consists essentially of"). It is explicitly contemplated that both the broader and narrower interpretations can be applied to all aspects and embodiments of the present invention. In other words, the word "comprising" and synonyms thereof may be replaced by the phrase "consisting of" or the phrase "consists essentially of" or synonyms thereof and *vice versa*.

25

30

The phrase, "consists essentially of" and its pseudonyms may be interpreted herein to refer to a material where minor impurities may be present. For example, the material may be greater than or equal to 90% pure, such as greater than 95% pure, such as greater than 97% pure, such as greater than 99% pure, such as greater than 99.9% pure, such as greater than 99.99% pure, such as greater than 99.999% pure, such as 100% pure.

35

As used herein, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "a composition" includes

mixtures of two or more such compositions, reference to “an oxygen carrier” includes mixtures of two or more such oxygen carriers, reference to “the catalyst” includes mixtures of two or more such catalysts, and the like.

- 5 When used herein, the term “hollow fibre membrane” refers to a semi-permeable barrier material in the form of a hollow fibre.

The HFM may be fabricated from diverse methods. For example, the methods for fabricating the HFM may include, but are not limited to, thermally induced phase separation, non-solvent
10 induced phase separation, vapor induced phase separation, electrospinning, melt spinning, and solution-spinning in which the main ingredients of the HFM are dissolved in an appropriate solvent.

As disclosed above, the force to fracture single hollow fibre membrane in the braided hollow
15 fibre membrane composite structure is greater than the force to fracture a single hollow fibre membrane that is not braided. For a single hollow fibre membrane, the force recorded is the force required to fracture the single hollow fibre membrane. For the braided hollow fibre membrane composite structure, although there are one or more (e.g. 1, 2, 3, 4, etc.) hollow
20 fibre membranes, the force recorded is the least force required to fracture at least one hollow fibre membrane.

In some embodiments of the present invention that may be mentioned herein, the braided hollow fibre membrane composite structure also comprised one or more reinforcing fibres, wherein the one or more hollow fibre membranes are co-braided with the one or more
25 reinforcing fibres.

In some embodiments of the present invention that may be mentioned herein, each of the one or more reinforcing fibres may be independently selected from one or more of the group consisting of a PSF (polysulfone), PES (polyethersulfone), PC (polycarbonate), PEI (poly
30 (ether imide)), PTFE (polytetrafluoroethylene), PAN (polyacrylonitrile), cellulose, cellulose derivatives, and, more particularly, metal (e.g. stainless steel), PP (polypropylene), PE (polyethylene), PVDF (polyvinylidene fluoride), nylon, PET (polyethylene terephthalate), and carbon fibres.

35 In further embodiments of the present invention that may be mentioned herein, if at least one of the one or more reinforcing fibres are formed from a same material as at least one of the one or more HFMs, then it may differ from the same material in the one or more hollow fibre

membranes in one or more of its thermal transition behaviour (e.g. one or more of glass transition temperature, melting temperature, and melt flow index), mechanical performance (e.g. strength, modulus and breakage strain), molecular weight, molecular weight distribution, and density. Thus, the reinforcing fibre may be a homogeneous reinforcement or a heterogeneous reinforcement to the HFM. As will be appreciated, when the reinforcing fibre is a heterogeneous reinforcement, apart from differing chemically, it may also differ mechanically in the manner noted above.

In certain embodiments that may be mentioned herein, when the one of the one or more reinforcing fibres are formed from a same material as at least one of the one or more hollow fibre membranes, then it may also be a hollow fibre membrane with identical properties. It will be appreciated that when there are two or more of the reinforcing fibres of the same material of the hollow fibre membrane, then one may essentially be an identical hollow fibre membrane with identical properties and the other reinforcing fibre may be a solid fibre or a hollow fibre with properties that differs from the same material in the one or more hollow fibre membranes in one or more of its thermal transition behaviour (e.g. one or more of glass transition temperature, melting temperature, and melt flow index), mechanical performance (e.g. strength, modulus and breakage strain), molecular weight, molecular weight distribution, and density.

When used herein, homogeneous reinforcement means that the reinforcing fibre is chemically the same as the HFM, despite the same or different molecular weight, molecular weight distribution between the HFM and reinforcing fibres. For example, a PP HFM may be reinforced by a PP fibre, and a PE HFM could be reinforced by a PE fibre, despite the same or different molecular weight, molecular weight distribution between the HFM and reinforcing fibres. In another example, a PVDF HFM may be reinforced by a PVDF fibre, and the reinforcing PVDF fibre may or may not have the same molecular weight, molecular weight distribution as the PVDF HFM.

When used herein, heterogeneous reinforcement means that the reinforcement fibre is chemically different to the HFM fibre. For example, a PP HFM may be reinforced by a PE fibre and a PE HFM may be reinforced by nylon fibres. The HFM fibre and the reinforcing fibre may be materials in the same category. More specifically, both the HFM fibre and the reinforcing fibre may be organic polymers. For example, PVDF fibre may be reinforced with PET fibres. Also, in some embodiments of the present invention that may be mentioned herein, the reinforcing fibre may be non-polymeric materials such as inorganic fibres including but not limited to carbon fibres, metal fibres, and composite fibres.

In some embodiments of the present invention that may be mentioned herein, the one or more hollow fibre membranes are co-braided with the one or more reinforcing fibres.

5 An example of forming a braided HFM composite structure is shown in FIG. 1. FIG. 1 shows the steps for making a relatively simple braided composite structure which contains two HFM and one reinforcing fibre. The two HFMs are labelled as 1 and 3, with the reinforcing fibre 2 laid in the middle (FIG. 1a). For the first step of braiding, HFM 3 overlaps over the reinforcing fibre 2 (FIG. 1b). For the second step, HFM 1 overlaps over HFM 3 (FIG. 1c). For the next
10 step, the braiding is repeated by overlapping the reinforcing fibre 2 over HFM 1. These steps are repeated according to the positions in FIGS. 1b-c to make the braided composite structure. FIG. 1d shows the final appearance of the relatively simple braided composite structure comprising two HFM and one reinforcing fibre.

15 Thus, the braided hollow fibre membrane composite structures disclosed herein may employ a relatively simple braiding pattern or design, such as a braided composite structure comprising one hollow fibre membrane and one reinforcing fibre, or a braided composite structure comprising two hollow fibre membranes and one reinforcing fibre.

20 It will be appreciated that the disclosed braided hollow fibre membrane composite structure may use a slightly complex braiding pattern or design, such as a braided composite structure comprising three HFM and one reinforcing fibre, a braided composite structure comprising two HFM and two reinforcing fibres, and a braided composite structure comprising three HFM and two reinforcing fibres.

25 An example of forming a slightly complex braided composite structure is shown in FIG. 2. FIG. 2 shows the steps for making a slightly complex braided composite structure, which contains two HFM and two reinforcing fibres. The two HFM are labelled as 1 and 2, while the two reinforcing fibres are labelled as 3 and 4 (FIG. 2a). For the first step, the reinforcing fibre 4 overlaps over the reinforcing fibre 3 (FIG. 2b). For the second step, HFM 2 overlaps over the reinforcing fibre 4 (FIG. 2c). For the third step, the reinforcing fibre 4 overlaps over HFM 1 (FIG. 2d). For the next step, the braiding is repeated from right side to the left side, that is, the reinforcing fibre 3 overlaps over HFM 2. These steps are repeated according to the positions in FIGS. 2b-d to make the braided composite structure. FIG. 2e shows the final appearance
30 of the slightly complex braided composite structure comprising two HFM and two reinforcing fibres.

In some embodiments of the present invention that may be mentioned herein, the force to fracture a single hollow fibre membrane in the braided HFM is greater than the force to fracture a single HFM that is not braided. The force to fracture a single braided HFM, or a single HFM, may be measured by mechanical testing by using a MTS Criterion Electromechanical Test System Model C43.

In some embodiments of the present invention that may be mentioned herein, the force to fracture a single hollow fibre membrane in the braided hollow fibre membrane may have a value that is at least 150% greater than the force to fracture a single hollow fibre membrane that is not braided, such as a value that is at least 200% greater.

Without wishing to be bound by theory, the mechanical performance and movement flexibility of a braided composite structure may be controlled by the compactness of the braiding, the number of strands used in the braiding, and the type of reinforcing fibres used in the braiding. When used herein, mechanical performance refers to the load required to fracture the HFM fibre. When used herein, movement flexibility refers to how easily the HFM fibre can be moved under a cleaning process, specifically under an aeration process, in various embodiments of the present invention that may be mentioned herein.

In some embodiments of the present invention that may be mentioned herein, a total number of fibres obtained by the addition of a total number of the one or more hollow fibre membranes and a total number of the one or more reinforcing fibres may be from 2 to 100, provided that there is at least one hollow fibre membrane and at least one reinforcing fibre. For example, the number of strands used in the braiding may be within 2 to 100, including both HFM and reinforcing fibres. Without wishing to be bound by theory, the physical properties of the reinforcing fibres, such as density and the modulus, may largely affect the movement flexibility of the braided composite structures. For example, a braided composite structure containing stainless-steel wire as the reinforcement shows apparently low movement flexibility due to the high modulus and low flexibility of stainless-steel wire.

In some embodiments of the present invention that may be mentioned herein, the total number of the one or more hollow fibre membranes may be from 1 to 99, such as from 2 to 6. Thus, the hollow fibre membrane may be a single strand or multiple strands in the braided hollow fibre membrane composite structure.

In some embodiments of the present invention that may be mentioned herein, the total number of the one or more reinforcing fibres may be from 1 to 99, such as from 1 to 3.

In some embodiments of the present invention that may be mentioned herein, each of the one or more hollow fibre membranes may be independently formed from an organic polymeric material that is capable of forming a hollow fibre membrane that can be used to separate at least two materials from one another in a fluid. For example, each of the one or more hollow fibre membranes may be independently formed from an organic polymeric material selected from one or more of the group consisting of PSF (polysulfone), PES (polyethersulfone), PC (polycarbonate), PEI (poly (ether imide)), PTFE (polytetrafluoroethylene), PAN (polyacrylonitrile), cellulose, cellulose derivatives and, more particularly, PVDF (polyvinylidene fluoride), PP (polypropylene), and PE (polyethylene).

In some embodiments of the present invention that may be mentioned herein, each of the one or more hollow fibre membranes may be independently a symmetric hollow fibre membrane or an asymmetric hollow fibre membrane. For example, all of the HFMs in the braided HFM composite structure may be all symmetric or may be all asymmetric. Whether the membrane is symmetric or asymmetric can be ascertained by the cross-section morphology of the HFM. When used herein, symmetric membranes refer to membranes having same cross section structure while asymmetric membranes have differentiated structures from the inner surface to the outer surface of the cross section. A typical asymmetric membrane may be a PVDF membrane, which may be fabricated by a phase separation method.

The reinforcing fibre may be termed other names such as wire, filament, strand, yarn and bundle. If the reinforcing fibre is composed of a group of thin fibres, the thin fibres may be pre-braided, not braided, pre-bundled together or not pre-bundled together. For example, if the reinforcing fibres are a group of very thin fibres, such as carbon fibres, they may be pre-braided before they are used in the hollow fibre braided composite structure, or they may be pre-bundled by other possible means other than braiding.

In some embodiments of the present invention that may be mentioned herein, each of the one or more reinforcing fibres may be independently in the form of a wire, a filament, a strand, and a yarn. Without wishing to be bound by theory, the movement flexibility and mechanical performances of braided HFM composite structure may be adjusted by reinforcing the wire, filament, strand, yarn or bundle of different materials, stiffness, strength, diameters, cross-section geometries of the one or more reinforcing fibres, and the reinforcing phase may be solid or hollow.

An example of forming another slightly complex braided composite structure is shown in FIG. 3. FIG. 3 shows the steps for making a slightly complex braided composite structure which contains three HFM and one strand of reinforcing fibres. The three HFM are labelled as 1, 2 and 3, while the reinforcing fibre is labelled as 4 (FIG. 3a). For the first step, the reinforcing fibre 4 overlaps over HFM 3 (FIG. 3b). For the second step, HFM 1 overlaps over HFM 2 and reinforcing fibre 4 (FIG. 3c). The braiding steps are repeated according to the positions in FIGS. 3b-c to make the braided composite structure. FIG. 3d shows the final appearance of the slightly complex braided composite structure comprising three HFM and one strand of reinforcing fibres.

10

In some embodiments of the present invention that may be mentioned herein, each of the one or more reinforcing fibres may be independently formed from an organic polymeric material, an inorganic material or a combination thereof.

15 In further embodiments of the present invention that may be mentioned herein, when there are two or more reinforcing fibres may provide a hybrid reinforcement. When used herein, hybrid reinforcement means that the reinforcing fibres are different types of reinforcing fibre. For example, when there are multiple reinforcing fibres, they may be made of different materials such as nylon and PE. Alternatively, the reinforcing fibres may be formed from different inorganic materials. Yet further embodiments that may be mentioned herein may make use of polymeric reinforcing fibres and inorganic reinforcing fibres.

FIG. 4 shows an alternative example of making another slightly complex braided composite structure. FIG. 4 shows the steps of making another slightly complex braided composite structure which contains three HFM and two reinforcing fibres, while the two reinforcing fibres are made of different materials. The three HFM are labelled as 1, 3 and 5, while the two reinforcing fibres are labelled as 2 and 4 (FIG. 4a). For the first step of braiding, HFM 1 overlaps over the reinforcing fibre 2, while HFM 5 overlaps over the reinforcing fibre 4 (FIG. 4b). For the second step, HFM 3 overlaps over HFM 1 (FIG. 4c). For the third step, HFM 1 overlaps over HFM 5 (FIG. 4d). The braiding steps are repeated according to the positions in FIGS. 4b-4d to make the braided composite structure. FIG. 4e shows the final appearance of the slightly complex braided composite structure comprising three HFM and two different reinforcing fibres.

35 In some embodiments of the present invention that may be mentioned herein, each of the one or more reinforcing fibres may be solid or hollow. In further embodiments of the present invention that may be mentioned herein, the reinforcing fibre may be a solid fibre or hollow

fibre with a lumen inside. For example, PP HFM may be reinforced by solid PE fibre, and may be reinforced by some other strong HFM fibres that have separation capabilities.

5 The compactness of the braided composite structures may be adjusted by adjusting the braiding angle. When used herein, the braiding angle is measured as a fibre angle relative to a longitudinal direction of the braided composite structure. Without wishing to be bound by theory, a smaller braiding angle results in loose braiding composite structures while a larger braiding angle leads to tight braiding composite structures. In a loosely braided composite structure, the HFM fibre has more freedom to elongate in the radial direction under stress, while the movement of the HFM fibre in a tightly braided composite structure is constrained by the reinforcing fibres.

15 In some embodiments of the present invention that may be mentioned herein, a braiding angle obtained at any point of the composite structure may have a value of from greater than 0 to less than 90°, such as from greater than 0 to 60°, such as from greater than 0 to 20°, such as from 20 to less than 90°, such as from 20 to 60°, such as from 60 to less than 90°.

In some embodiments of the present invention that may be mentioned herein, an average braiding angle may be 18.1 and 22.8° based on the statistic value of 20 measurements.

20

In some embodiments of the present invention that may be mentioned herein, the braided HFM composite structures may use a more complex braiding pattern or design, such as in a braided composite structure comprising five HFM and two reinforcing fibres.

25 An example of forming a more complex braiding structure is shown in FIG. 5. FIG. 5 shows the steps of making a more complex braiding structure which contains five HFM and two reinforcing fibres. The five HFM are labelled as 1, 2, 4, 6 and 7, while the two reinforcing fibres are labelled as 3 and 5 (FIG. 5a). For the first step of braiding, HFM 1 overlaps over HFM 2, while HFM 7 overlaps over HFM 6 (FIG. 5b). For the second step, the reinforcing fibre 3 overlaps over HFM 1 and the reinforcing fibre 5 overlaps over HFM 7 (FIG. 5c). For the third step, HFM 1 overlaps over HFM 4 (FIG. 5d). For the fourth step, HFM 7 overlaps over HFM 1 (FIG. 5e). The braiding steps are repeated according to the positions in FIGS. 5b-5e to make the braided composite structure. FIG. 5f shows the final appearance of the more complex braided composite structure comprising five HFM and two reinforcing fibres.

35

In embodiments of the invention, a maximum deflection of the braided hollow fibre membrane composite structure may accounts for from 0% to 80% of the length of braided hollow fibre

membrane composite structure, such as from 10% to 53%, such as from 20% to 61%. An appropriate deflection of braided hollow fibre membrane composite structures enables effective cleaning and reduce fouling under aeration over a long duration of operation without causing mechanical damage to the membrane. The deflection of the braided composite structures can be adjusted by reinforcing the wire, filament, strand, yarn or bundle using different materials, or by modifying the stiffness, strength, diameters, cross-section geometries of the one or more reinforcing fibers, and the reinforcing fibers may be hollow or solid. As such, the desired maximum deflection under aeration cleaning may be adjusted to a desired amount for any particular use.

10

In some embodiments of the present invention that may be mentioned herein, the braided hollow fibre membrane composite structure may be selected from the list:

selected from the list

- (a) two or more polypropylene hollow fibre membranes;
- 15 (b) two or more polyethylene hollow fibre membranes;
- (c) two or more PVDF hollow fibre membranes; and, more particularly,
- (d) one or more PVDF hollow fibre membranes and one or more PVDF reinforcing fibres;
- (e) one or more PP hollow fibre membranes and one or more PP reinforcing fibres;
- (f) one or more PE hollow fibre membranes and one or more PE reinforcing fibres;
- 20 (g) one or more PP hollow fibre membranes and one or more PE reinforcing fibres;
- (h) one or more PE hollow fibre membranes and one or more nylon reinforcing fibres;
- (i) one or more PVDF hollow fibre membranes and one or more PET reinforcing fibres;
- (j) one or more PP hollow fibre membranes and one or more metal wire reinforcing fibres;
- (k) one or more PVDF hollow fibre membranes and one or more PE reinforcing fibres;
- 25 (l) one or more PE hollow fibre membranes and one or more metal wire reinforcing fibres;
- (m) one or more PP hollow fibre membranes and one or more nylon reinforcing fibres;
- (n) one or more PE hollow fibre membranes, one or more nylon reinforcing fibres, and one or more strands of carbon fibre reinforcing fibres; and
- 30 (o) one or more PE hollow fibre membranes, and one or more strands of carbon fibre reinforcing fibres.

In further embodiments of the present invention that may be mentioned herein, the braided hollow fibre membrane composite structure may be selected from the list:

- (ai) three polypropylene hollow fibre membranes, where at least one of the three polypropylene hollow fibre membranes is a reinforcing fibre;
- 35 (a) three PE hollow fibre membranes and one hollow PP reinforcing fibre;

- (aiii) three PE hollow fibre membranes, one solid PE reinforcing fibre, and one strand of carbon fibre reinforcing fibre and, more particularly,
- (aiv) two PE hollow fibre membranes and two PE reinforcing fibres (e.g. two solid PE reinforcing fibres);
- 5 (av) six PP hollow fibre membranes and one metal wire reinforcing fibre (e.g. one solid metal wire reinforcing fibre);
- (avi) two PVDF hollow fibre membranes and three PE reinforcing fibres (e.g. three solid PE reinforcing fibres);
- (avii) two PE hollow fibre membranes and one PE reinforcing fibre (one solid PE reinforcing
- 10 fibre);
- (aviii) five PP hollow fibre membranes and two nylon reinforcing fibres (e.g. two solid nylon reinforcing fibres); and
- (aix) three PE hollow fibre membranes, and one strand of carbon fibre reinforcing fibre.

- 15 As will be appreciated, the braiding of HFM with reinforcing fibres having excellent mechanical properties and other desirable physical properties, advantageously and significantly increase the force to fracture the HFM.

In a second aspect of the invention, there is provided a method of forming a braided hollow

20 fibre membrane composite structure as described above, wherein the method comprises:

- (bi) one or more hollow fibre membranes and one or more reinforcing fibres; and
- (bii) intertwining the one or more one or more hollow fibre membranes with the one or more reinforcing fibres a plurality of times to form the braided hollow fibre membrane composite structure.

25

In some embodiments of the present invention that may be mentioned herein, the methods of forming a braided hollow fibre membrane composite structure may be as depicted in any one of FIGS. 1 to 5, with the processes as discussed herein.

30

As also will be appreciated, the one or more hollow fibre membranes may be intertwined with the one or more reinforcing fibres a plurality of times until the desired properties are obtained for the braided hollow fibre membrane composite structure. For example, the one or more hollow fibre membranes may be intertwined with the one or more reinforcing fibres at least 10

35 times to make a meaningful length of the braided hollow fibre membrane composite structure. It will be appreciated that if the fibre is continuous, the online braiding on the production line can also be continuous without a certain up limit number.

The description of various embodiments in this disclosure are presented for the purpose of demonstration and illustration yet are not intended to be exhaustive. Those who skilled in the art would readily know how to fabricate more complicated braided composite structures using different HFM fibres, reinforcing fibres, patterns and designs to cater to applications requiring various mechanical performance and movement flexibility. According to various embodiments, the relatively simple, slightly complex, complex and even more complex braided composite structures can be manufactured by any suitable method. This may be accomplished manually or via highly automated machines. As will be appreciated, extremely complicated braided composite structures may be preferably be made by highly automated and intelligent appliances. The braided composite structures can be made with pre-existing HFM and reinforcing fibres, or else can be fabricated *in situ* when the HFM are being produced.

While the present invention has been described in exemplary embodiments, it should be understood by those skilled in the art that many variations in the details may be made without departing from the scope of the present invention as defined in the following statements.

1. Braided HFM composite structures comprising one or more HFM braided with one or more reinforcing fibres;
2. Braided HFM composite structures of statement 1, whereas the fracture load of HFM could be effectively increased;
3. Braided HFM composite structures of statement 1, whereas the movement flexibility of HFM could be adjusted by by the compactness of the braiding, the number of strands used in the braiding and the type of reinforcing fibres used in the braiding;
4. Braided HFM composite structures of statement 1, whereas the compactness of the braided composite structures can be adjusted by the fibre angle relative to longitudinal direction of the braided composite structures;
5. Braided HFM composite structures of statement 1, whereas the braiding angle can lie in the range $0^{\circ} < \text{angle} < 90^{\circ}$, while the preferred braiding angle is in the range of 20° - 60° ;
6. Braided HFM composite structures of statement 1, whereas the number of total strands including both HFM and reinforcing fibres can be within 2~100;
7. Braided HFM composite structures of statement 1, whereas the HFM could be mechanically enhanced by reinforcing wire, filament, strand, yarn or bundle of different materials, stiffness, strength, diameters, cross-section geometries;
8. Braided HFM composite structures of statement 1, whereas the HFM can be symmetric or asymmetric membranes;

9. Braided HFM composite structures of statement 1, whereas the HFM can be manufactured by phase separation approach, electrospinning, melt spinning or solution spinning;
10. Braided HFM structures of statement 1, whereas the reinforcing fibers can be made of organic polymers or inorganic fibers or hybrids;
11. Braided HFM composite structures of statement 1, whereas the reinforcing fibers can be metal fibers, carbon fibers or composite fibers;
12. Braided HFM composite structures of statement 1, whereas the reinforcing fibers can be solid fibre or hollow fibre with lumen inside and capable of separation of fluids;
13. Braided HFM composite structures of statement 1, whereas the reinforcing fibers can be more than one type and hybrid reinforcement in cases that the number of reinforcing fibres is equal to or larger than 2;
14. A method of providing braided HFM composite structures, which is comprised of braiding one or more HFM braided with one or more reinforcing fibres;
15. A method of providing braided HFM composite structures of statement 14, whereas the HFM overlap over or under the reinforcing fibers to form the braided composite structures.

It will be appreciated that, contributed by the excellent mechanical performance of reinforcing fibres, the fracture load of HFM could be significantly increased in the braided composite structures in comparison to individual HFM fibres that are not braided. By designing the composite structure properties and the compactness between HFM and reinforcing fibres, the deflection of braided composite structures under water flow could be well controlled, prolonging the membrane lifespan through better mechanical properties while realizing effective fouling control by cleaning process.

Further aspects and embodiments of the invention will now be discussed by reference to the following non-limiting examples.

Examples

Materials

All materials/reagents were obtained from commercial sources and used without further modifications/purification.

- PP hollow fibre (outer diameter of 470 μm) - Zena Membranes (Czech republic)
- PE hollow fibre (outer diameter of 0.5 mm) - Kitz Micro Filter Corporation (Japan)
- PE solid fibre (diameter of 0.5 mm, fracture load of 450 N) - Bingolife.

- PVDF hollow fibre (outer diameter of 2.2 mm) - Ceraflo Pte Ltd (Singapore)
Nylon reinforcing fibre (diameter of 0.33 mm) - YGK (Japan)
Carbon reinforcing fibre (1k), Besfight HTA-W1K-H50 - Toho Tenax Co., Ltd.
Stainless steel reinforcing fibre (diameter of 0.33 mm) - American Fishing Wire
5 Isopropyl alcohol - Aik Moh (Singapore)

Example 1

- The braided HFM composite structures were characterized by mechanical properties,
10 deflection and filtration test.

Mechanical testing

- Mechanical testing was performed by MTS Criterion Electromechanical Test System Model
C43. The maximum strain recorded is the position where the braiding structure fractures.
15

Deflection test

- Deflection test was conducted to study the movement behavior of the braided composite
structures under water, simulating the air scouring process for membranes. The deflection test
was performed by using an aerator and the maximum deflection was measured. To be more
20 specific, the setup was submerged in water with an aerator fixed at the bottom of the tank.
Fibers with length of 5cm were placed parallel to the aerator onto a stand and the deflection
was measured from the highest point of the fiber to its original position. Details of the setup is
shown in FIG. 6.

25 *Filtration test*

- Filtration test was performed to assess the flux and permeance of the braided HFM composite
structures. The braided HFM composite structures were potted with epoxy into tubes of 5 –
10 mm in diameter. Then, these braided HFM composite structures were wetted by soaking
them in isopropyl alcohol or ethanol for at least 4 hours before the tests. Filtration was carried
30 out by submerging the hollow fibers into a beaker containing distilled water, and applying a
suction force with a peristaltic pump. The negative pressure exerted was measured by a
pressure gauge.

- The permeability is defined as the rate of diffusion of molecules or ions across the membrane.
35 In the application of filtration membranes, the permeability of the braided composite structure
can be determined by using the following equation:

$$L_p = \frac{J}{\Delta P}$$

where L_p is the permeability ($\frac{\text{Liters}}{\text{m}^2 \cdot \text{hours} \cdot \text{bar}}$), J is the filtrate flux rate ($\frac{\text{Liters}}{\text{m}^2 \cdot \text{hours}}$), and ΔP is the pressure applied across the membrane (bar). Filtration was performed at transmembrane pressures ranging from 0.05 to 2 bar and the permeate is collected and weighed to determine the average flux.

Example 2

A braided HFM composite structure comprising two PE HFM and two reinforcing PE solid fibers was fabricated according to the method depicted in FIG. 2. The reinforcing PE solid fibre has a fracture load of 450 N. A digital image of the braided HFM composite structure is shown in FIG. 7. The braiding angle was measured to be 18.1°. The fracture load of the PE HFM in the braided HFM composite structures was at an average of 419.7 N while a single PE HFM without braiding averaged at 1.0 N. The braiding of fibers resulted in an increase of 41870% in fracture load while no appreciable change in maximum strain was observed. Deflection tests for the braided composite structure and a bundle of four unbraided PE HFM and a single PE HFM were carried out and the results are shown in FIGS. 8-10. The maximum deflection measured for the bundle of four unbraided PE HFM was 1.50 cm and the single PE HFM was 2.50 cm, while the PE HFM in braided structure was 2.65 cm, which is 53% of the length of braided HFM composite structure. A high permeability of 1810.1 Lmh/bar was recorded for the braided HFM composite structures comprising two PE HFM and two reinforcing PE fibers.

Example 3

A braided HFM composite structure comprising six PP HFM and one reinforcing solid stainless steel wire was fabricated according to the method depicted in FIG. 5. The reinforcing stainless steel wire has a modulus of ~200 GPa, fracture load of 166N, and density of ~8 g/cm³. A digital image of the braided HFM composite structure is shown in FIG. 11. The braiding angle of PP HFM was measured to be 25.2°. The fracture load of a single PP HFM without braiding averaged at 3.4 N compared to the fracture load of PP HMF in the braided composite structure with an average of 56.2 N. The braiding of fibers resulted in an increase of 1553% in fracture load while no appreciable change in breakage strain was observed. Deflection tests were carried out for both PP HFM in the braided structure and the bundle of six unbraided PP HFM, as shown in FIGS. 12 and 13. The maximum deflection measured for the bundle of six unbraided PP HFM was 3.80 cm while the PP HFM in braided structure was 0 cm, due to the high modulus and high density of the reinforcing metal wire.

Example 4

A braided HFM composite structure comprising two PVDF HFM and three reinforcing PE solid fibers was fabricated according to the method depicted in FIG. 4. A digital image of the braided HFM composite structure is shown in FIG. 14. The braiding angle of the PE reinforcing fibre was measured to be 29.0°. The fracture load of a single PVDF HFM was calculated to have an average of 159.7 N without braiding compared to the PVDF HFM in the braided composite structure of an average of 395.6 N, indicating an increase of 148% in fracture load with the braiding. Deflection tests were carried out for both the PVDF HFM in the braided structure and a bundle of 2 unbraided PVDF HFM, as shown in FIGS. 15 and 16. The maximum deflection measured for the bundle of two unbraided PVDF HFM was 1.00 cm while the PVDF HFM in braided composite structure was 0.50 cm which is 10% of the length of the braided HFM composite structure comprising two PVDF HFM and three reinforcing PE solid fibers.

Example 5

A braided HFM composite structure comprising two PP HFM and one reinforcing PE solid fiber was fabricated according to the method depicted in FIG. 1. A digital image of the braided HFM composite structure is shown in FIG. 17. The braiding angle was measure to be around 10.9°. The fracture load of a single PP HFM without braiding has an average value of 3.4 N while the PP HFM in the braided composite structure has average fracture load of 251.7 N. Deflection tests were carried out for the PP HFM in the braided structure, a bundle of three unbraided PP HFM, and a single PP HFM, as shown in FIGS. 18-20. The maximum deflection measured for the bundle of three unbraided PP HFM was 1.50 cm and the single PP HFM was 2.00 cm, while the PP HFM in braided composite structure was 3.05 cm which is 61% of the length of the braided HFM composite structure comprising two PP HFM and one reinforcing PE solid fiber.

Example 6

A braided HFM composite structure comprising three PP HFM was fabricated according to the method depicted in FIG. 1. A digital image of the braided HFM composite structure is shown in FIG. 21. The braiding angle was measured to be 12.2°. According to the mechanical test, the fracture load to fracture the PP HFM in the braided structure comprising of three PP HFM tripled the fracture load to break a single PP HFM without braiding. The fracture load of a single PP HFM without braiding has an average value of 3.4 N while the PP HFM in the braided

composite structure comprising three PP HFM has an average fracture load of 10.4 N, surprisingly, with a standard deviation of 0.3 N.

Example 7

5

A braided HFM composite structure comprising three PE HFM and one reinforcing PP HFM was fabricated according to the method depicted in FIG. 3. A digital image of the braided HFM composite structure is shown in FIG. 22. The braiding angle was measured to be 12.6°. According to the mechanical test, the fracture load to fracture the PP HFM in the braided HFM composite structure comprising three PE HFM and one reinforcing PP HFM is nearly 400% the fracture load value to break a single PE HFM without braiding. the fracture load of a single PE HFM without braiding has an average value of 1 N while the PE HFM in the braided composite structure comprising three PE HFM and one reinforcing PP HFM has average fracture load of 4.05 N.

15

Example 8

A braided HFM composite structure comprising five PP hollow fibers and two reinforcing solid nylon fibers was fabricated according to the method depicted in FIG. 5. The nylon reinforcing fibre has a fracture load of 156 N. A digital image of the braided HFM composite structure is shown in FIG. 23. The braiding angle was measured to be 22.8°. The fracture load of a single PP HFM without braiding averaged at 3.4 N, while the PP HFM in the braided composite structure has an average value of 171.6 N. Deflection tests were carried out for the PP HFM in the braided structure and the bundle of five unbraided PP HFM, as shown in FIGS. 24 and 25. The maximum deflection measured for the bundle of five unbraided PP HFM and PP HFM in braided structure were 1.00 and 1.55 cm, which are 20% and 31% of the length of specimen tested, respectively. A filtration permeability of 130.7 Lmh/bar was recorded for the braided composite structure comprising five PP HFM and two reinforcing nylon fibers.

Example 9

A braided HFM composite structure comprising three PE HFM, one strand of reinforcing carbon fiber, and one reinforcing PE solid fiber, was fabricated according to the method depicted in FIG. 4. The carbon reinforcing fibre (1k), Besfight HTA-W1K-H50 has a tensile strength of 3720 MPa, modulus of 235 GPa and density of 1.76g/cm³. A digital image of the braided HFM composite structure is shown in FIG. 26. The braiding angle was calculated to be 28.7°. Deflection tests were carried out for the PE HFM in the braided structure and the

35

bundle of four unbraided PE HFM, as shown in FIGS. 27 and 9. The maximum deflection measured for the bundle of four unbraided PE HFM and the braided composite structure were 1.50 and 3.05 cm, respectively.

5 Example 10

A braided HFM composite structure comprising three PE HFM and one strand of reinforcing carbon fiber was fabricated according to the method depicted in FIG. 3. A digital image of the braided HFM composite structure is shown in FIG. 28. The braiding angle was measured to
10 be 15.2°. The fracture load of a single PE HFM without braiding averaged at 1.0 N while the PE HFM in the braided composite structure has an average value of 4.8 N, achieving an increase of 380% in fracture load. Deflection tests were carried out for the braided structure and the bundle of three unbraided PE HFM, as shown in FIGS. 29 and 30. The maximum
15 deflection measured for the bundle of three unbraided PE HFM was 2.30 cm while the braided composite structure was 3.20 cm which is 64% of the total length of the braided HFM composite structure.

Taken together, the braiding of HFMs with different reinforcing fibers can effectively enhance the mechanical performance while having controlled fiber movement during aeration. The said
20 braided hollow fibre membrane composite structures could be further explored to enhance the mechanical properties of HFM and enable long-term damage-free operation and/or cleaning of membranes.

Claims

1. A braided hollow fibre membrane composite structure, comprising:
one or more hollow fibre membranes; and
one or more reinforcing fibres, wherein
the one or more hollow fibre membranes are co-braided with the one or more reinforcing fibres,
wherein the force to fracture a single hollow fibre membrane in the braided hollow fibre
membrane composite structure is greater than the force to fracture a single hollow fibre
membrane that is not braided.
2. The braided hollow fibre membrane composite structure according to Claim 1, wherein
the force to fracture the single hollow fibre membrane in the braided composite structure has
a value that is at least 150% greater than the force to fracture a single hollow fibre membrane
that is not braided, such as a value that is at least 200% greater.
3. The braided hollow fibre membrane composite structure according to Claim 1 or Claim
2, wherein a total number of fibres obtained by the addition of a total number of the one or
more hollow fibre membranes and a total number of the one or more reinforcing fibres is from
2 to 100, provided that there is at least one hollow fibre membrane and at least one reinforcing
fibre.
4. The braided hollow fibre membrane composite structure according to Claim 3, wherein
the total number of the one or more hollow fibre membranes is from 1 to 99, such as from 2 to
6.
5. The braided hollow fibre membrane composite structure according to Claim 3, wherein
the total number of the one or more reinforcing fibres is from 1 to 99, such as from 1 to 3.
6. The braided hollow fibre membrane composite structure according to any one of the
preceding claims, wherein each of the one or more hollow fibre membranes is independently
formed from an organic polymeric material that is capable of forming a hollow fibre membrane
that can be used to separate at least two materials from one another in a fluid.
7. The braided hollow fibre membrane composite structure according to Claim 6, wherein
each of the one or more hollow fibre membranes is independently formed from an organic
polymeric material selected from one or more of the group consisting of PSF (polysulfone),
PES (polyethersulfone), PC (polycarbonate), PEI (poly (ether imide)), PTFE

(polytetrafluoroethylene), PAN (polyacrylonitrile), cellulose, cellulose derivatives and, more particularly, PVDF (polyvinylidene fluoride), PP (polypropylene), and PE (polyethylene).

8. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein each of the one or more hollow fibre membranes is independently a symmetric hollow fibre membrane or an asymmetric hollow fibre membrane, optionally wherein all of the hollow fibre membranes in the braided hollow fibre membrane composite structure are all symmetric or are all asymmetric.

9. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein each of the one or more reinforcing fibres is independently in the form of a wire, a filament, a strand, and a yarn.

10. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein each of the one or more reinforcing fibres is independently formed from an organic polymeric material, an inorganic material or a combination thereof.

11. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein each of the one or more reinforcing fibres is solid or hollow.

12. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein each of the one or more reinforcing fibres is independently selected from one or more of the group consisting of a PSF (polysulfone), PES (polyethersulfone), PC (polycarbonate), PEI (poly (ether imide)), PTFE (polytetrafluoroethylene), PAN (polyacrylonitrile), cellulose, cellulose derivatives, and, more particularly, metal (e.g. stainless steel), PP (polypropylene), PE (polyethylene), PVDF (polyvinylidene fluoride), nylon, PET (polyethylene terephthalate), and carbon fibres.

13. The braided hollow fibre membrane composite structure according to Claim 12, wherein one or more of the following apply:

(aa) when the one of the one or more reinforcing fibres are formed from a same material as at least one of the one or more hollow fibre membranes, then it is also a hollow fibre membrane with identical properties; and

(bb) when wherein if at least one of the one or more reinforcing fibres are formed from a same material as at least one of the one or more hollow fibre membranes, then it differs from the same material in the one or more hollow fibre membranes in one or more of its thermal transition behaviour (e.g. one or more of glass transition temperature, melting temperature,

and melt flow index), mechanical performance (e.g. strength, modulus and breakage strain), molecular weight, molecular weight distribution, and density.

14. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein a braiding angle obtained at any point of the composite structure has a value of from greater than 0 to less than 90°, such as from 20 to 60°, where the braiding angle is measured as a fibre angle relative to a longitudinal direction of the braided composite structure.

15. The braided hollow fibre membrane composite structure according to Claim 14, wherein an average braiding angle is from 10 to 30° based on the average value of 10 braiding angle measurements, such as 12.6°.

16. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein a maximum deflection of the braided hollow fibre membrane composite structure accounts for from 0% to 80% of the length of the braided hollow fibre membrane composite structure, such as from 10% to 53%, such as from 20% to 61%.

17. The braided hollow fibre membrane composite structure according to any one of the preceding claims, wherein the braided hollow fibre membrane composite structure is selected from the list:

- (a) two or more polypropylene hollow fibre membranes;
- (b) two or more polyethylene hollow fibre membranes;
- (c) two or more PVDF hollow fibre membranes;
- (d) one or more PVDF hollow fibre membranes and one or more PVDF reinforcing fibres;
- (e) one or more PP hollow fibre membranes and one or more PP reinforcing fibres;
- (f) one or more PE hollow fibre membranes and one or more PE reinforcing fibres;
- (g) one or more PP hollow fibre membranes and one or more PE reinforcing fibres;
- (h) one or more PE hollow fibre membranes and one or more nylon reinforcing fibres;
- (i) one or more PVDF hollow fibre membranes and one or more PET reinforcing fibres;
- (j) one or more PP hollow fibre membranes and one or more metal wire reinforcing fibres;
- (k) one or more PVDF hollow fibre membranes and one or more PE reinforcing fibres;
- (l) one or more PE hollow fibre membranes and one or more metal wire reinforcing fibres;
- (m) one or more PP hollow fibre membranes and one or more nylon reinforcing fibres;
- (n) one or more PE hollow fibre membranes, one or more nylon reinforcing fibres, and one or more strands of carbon fibre reinforcing fibres; and

(o) one or more PE hollow fibre membranes, and one or more strands of carbon fibre reinforcing fibres.

18. The braided hollow fibre membrane composite structure according to Claim 17, wherein the braided hollow fibre membrane composite structure is selected from the list:

- (ai) three polypropylene hollow fibre membranes, where at least one of the three polypropylene hollow fibre membranes is a reinforcing fibre;
- (aii) three PE hollow fibre membranes and one hollow PP reinforcing fibre;
- (aiii) three PE hollow fibre membranes, one solid PE reinforcing fibre, and one strand of carbon fibre reinforcing fibre;
- (aiv) two PE hollow fibre membranes and two PE reinforcing fibres (e.g. two solid PE reinforcing fibres);
- (av) six PP hollow fibre membranes and one metal wire reinforcing fibre (e.g. one solid metal wire reinforcing fibre);
- (avi) two PVDF hollow fibre membranes and three PE reinforcing fibres (e.g. three solid PE reinforcing fibres);
- (avii) two PE hollow fibre membranes and one PE reinforcing fibre (one solid PE reinforcing fibre);
- (aviii) five PP hollow fibre membranes and two nylon reinforcing fibres (e.g. two solid nylon reinforcing fibres); and
- (aix) three PE hollow fibre membranes, and one strand of carbon fibre reinforcing fibre.

19. A method of forming a braided hollow fibre membrane composite structure as described in any one of Claims 1 to 18, wherein the method comprises:

- (bi) one or more hollow fibre membranes and one or more reinforcing fibres; and
- (bii) intertwining the one or more hollow fibre membranes with the one or more reinforcing fibres a plurality of times to form the braided hollow fibre membrane composite structure.