transfer to the culture at the membrane-culture contact surface.[10-12]

[0004] While porous and non-porous membranes have been applied in cell culture, only low densities have been achieved (i.e., <20e6 cells/mL) due to limitations in membrane design and challenges associated with membrane operation.[13] For example, in the case of porous membranes, the cell culture can be injured due to the formation of micron-sized bubbles that can emerge if the gas and culture pressures are improperly balanced with one another. Conversely, in the case of non-porous membranes, the mass transfer of gas molecules there through is slow thereby preventing sufficient gas exchange to support high density cultures.

[0005] To overcome the many challenges associated with sparging-based gas exchange processes in high-density cell culture, alternate methods and materials for bubble-free gas exchange are needed.

SUMMARY

[0006] Generally, this disclosure relates to bioreactors, and to bioprocessing methods using bioreactors. The present disclosure relates in part to the surprising finding that by replacing the sparger (e.g., used for oxygenation and/or introduction of gasses into a cell culture) of a high density cell culture bioreactor with one or more hollow-fiber membrane modules, sustained levels of dissolved oxygen (e.g., 60% DO) could be achieved at high cell densities (e.g., at least 120 X 10^6 cells/mL) without severe effects on culture health during operation. As a result, cells used in bioprocessing are maintained in a viable condition throughout the process, thereby increasing the productivity of a bioreactor.

[0007] In one aspect, the disclosure provides a method of culturing cells in a bioreactor comprising providing a mass transfer of a gas to/from the bioreactor without generating bubbles inside the bioreactor. In certain examples, the bioreactor is a perfusion bioreactor. The bioreactor can also be a batch-fed bioreactor.

[0008] In certain examples, the mass transfer of a gas to/from the bioreactor is provided by a gas transfer module. In various examples, the gas transfer module comprises a non-porous membrane, which can be, for example, a polymer, metal, or ceramic. Polymers can include silicone gum homopolymer, polydimethylsiloxane (PDMS), or silicone-

polycarbonate copolymer. In various examples, the non-porous membrane comprises a plurality of hollow fibers.

[0009] In various examples, the gas transfer module comprises a first flow path through the hollow fibers for passage of one or more gases and a second flow path around the hollow fibers for a flow of cell culture media and/or cells.

[00010] In other examples, the gas transfer module is located outside of the bioreactor.

[00011] In certain examples, the plurality of hollow fibers provide a flow path for culture media and cells to travel through spaces separating the hollow fibers. The spaces can be homogenous or heterogenous. The spaces can be of sufficient size to allow passage of a cell without causing shear forces on the cell. In certain examples, the spaces comprise a distance of about 15 µm to about 2000 µm. In certain other examples, the spaces comprise a distance 15-30 µm, 20-40 µm, 30-60 µm, 40-80 µm, 60-120 µm, 80-160 µm, 100-200 µm, 150-300 µm, 200-400 µm, 200-500 µm, 200-600 µm, 200-700 µm, 200-800 µm, 200-900 µm, 200-1000 µm, or 500-2000 µm, or a combination thereof.

[00012] In various examples, the flow of cell culture media and/or cells comprises tangential, axial flow or a combination thereof. The flow of the cell culture media and/or cells can be at a rate that is sufficient to maintain culture homogeneity without causing shear forces on the cells.

[00013] In various examples, the gasses can be carbon dioxide, oxygen, or nitrogen, or other gasses or even air.

[00014] In various examples, the bioreactor comprises a cell density of about 20 x 10^6 cells/ml, about 30 x 10^6 cells/ml, about 40 x 10^6 cells/ml, about 50 x 10^6 cells/ml, about 60 x 10^6 cells/ml, about 70 x 10^6 cells/ml, about 80 x 10^6 cells/ml, about 90 x 10^6 cells/ml, about 100 x 10^6 cells/ml, about 110 x 10^6 cells/ml, about 120 x 10^6 cells/ml, about 130 x 10^6 cells/ml, about 140 x 10^6 cells/ml, about 150 x 10^6 cells/ml, about 160 x 10^6 cells/ml, about 170 x 10^6 cells/ml, about 180 x 10^6 cells/ml, about 190 x 10^6 cells/ml, about 200 x 10^6 cells/ml, about 210 x 10^6 cells/ml, about 220 x 10^6 cells/ml, about 230 x 10^6 cells/ml, about 240 x 10^6 cells/ml, or about 250 x 10^6 cells/ml.

[00015] In various examples, the method avoids production of foam and/or

requires no anti-foaming agent during cell culture.

[00016] In other examples, the bioreactor comprises no headspace or substantially no headspace.

[00017] In various examples, the bioreactor comprises two or more gas transfer modules. The two or more gas transfer modules can provide mass transfer of different gases comprising oxygen, carbon dioxide, or nitrogen gas, and even air.

[00018] In another aspect, the disclosure provides a bioreactor system for high-density cell culture comprising a bioreactor vessel for growing cells in cell culture media and a liquid flow path in fluid communication with the bioreactor vessel, wherein the liquid flow path forms a circuit exterior to the bioreactor vessel for translocating cell culture media through a first and a second membrane gas transfer module.

[00019] In various examples, the first membrane gas transfer module is for adding oxygen to the cell culture media.

[00020] In other examples, the second membrane gas transfer module is for stripping carbon dioxide from the cell culture media.

[00021] In still other examples, the first membrane gas transfer module comprises a oxygen flow path and a cell culture medium flow path, wherein the gas flow path and cell culture flow path are separated by a gas-permeable membrane.

[00022] In still other examples, the first membrane gas transfer module comprises an air/carbon dioxide flow path and a cell culture medium flow path, wherein the air/carbon dioxide flow path and cell culture flow path are separated by a gas-permeable membrane.

[00023] The liquid flow path of the bioreactors described herein forms a circuit further comprising one or more additional elements, which can include a cell harvesting filter, a perfusion pump, a source of oxygen, a source of air/carbon dioxide, an oxygen sensor and/or a pH sensor.

[00024] In various examples of the bioreactors described herein, the cells of the high-density cell culture are at a density of about 20 x 10^6 cells/ml, about 30 x 10^6 cells/ml, about 40 x 10^6 cells/ml, about 50 x 10^6 cells/ml, about 60 x 10^6 cells/ml, about 70 x 10^6 cells/ml, about 80 x 10^6 cells/ml, about 90 x 10^6 cells/ml, about 100 x 10^6 cells/ml, about 110 x 10^6 cells/ml, about 120 x 10^6 cells/ml, about 130 x 10^6 cells/ml, about 140 x 10^6 cells/ml,

about 150 x 10^6 cells/ml, about 160 x 10^6 cells/ml, about 170 x 10^6 cells/ml, about 180 x 10^6 cells/ml, about 190 x 10^6 cells/ml, about 200 x 10^6 cells/ml, about 210 x 10^6 cells/ml, about 220 x 10^6 cells/ml, about 230 x 10^6 cells/ml, about 240 x 10^6 cells/ml, or about 250 x 10^6 cells/ml.

[00025] In various examples, the first and second membrane gas transfer modules add and/or remove gasses to/from the cell culture medium without forming bubbles.

[00026] The details of one or more examples of the disclosure are set forth in the description below. Other features or advantages of the present disclosure will be apparent from the following drawings and detailed description of several embodiments, and also from the appending claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[00027] The following drawings form part of the present specification and are included to further demonstrate certain aspects of the present disclosure, which can be better understood by reference to one or more of these drawings in combination with the detailed description of specific embodiments presented herein.

[00028] FIG. 1A provides a schematic of a bioreactor 100 known in the art comprising a sparger (or microsparger) 106 and a source of oxygen/air/carbon dioxide or other gases 110 for gas transfer to the cell culture 103. The prior art bioreactor 100 forms or produces bubbles or microbubbles 107 during the gas transfer process, which are harmful to the cells of the culture and can result in foaming, and thus, low cell density and/or cell culture product yields.

[00029] FIG. 1B shows a schematic of an embodiment of the bioreactors disclosed herein. In this embodiment, an improved bioreactor 300 includes one or more exterior-located membrane gas transfer modules 309 which are fed cell culture along a flow path 314 from/to the bioreactor in series by a pump 312. The first membrane gas transfer module 309b has a gas input 310b and gas exhaust 311b. The second membrane gas transfer module 309a also has a gas input 310a and a gas exhaust 311a. The pump 312 moves the cell culture from the bioreactor 300 along the flow path 314 (i.e., recirculation loop) through the first membrane gas transfer module 309b and then through the second membrane gas transfer module 309a, allowing the cell culture to interact with the gasses flowing through the membrane modules,

CLAIMS

1. A method of culturing cells in a bioreactor comprising providing a mass transfer of a gas to/from the bioreactor without generating bubbles inside the bioreactor.

2. The method of claims 1, wherein the bioreactor is a perfusion bioreactor or a batch-fed bioreactor.

3. The method of claim 1 or 2, wherein the mass transfer of a gas to/from the bioreactor is provided by a gas transfer module, preferably wherein the gas transfer module comprises a non-porous membrane, more preferred wherein the non-porous membrane is a polymer, metal, or ceramic, most preferred wherein the polymer comprises silicone gum homopolymer, polydimethylsiloxane (PDMS), or silicone-polycarbonate copolymer and/or wherein the non-porous membrane comprises a plurality of hollow fibers.

4. The method of claim 3, wherein the gas transfer module comprises a first flow path through the hollow fibers for passage of one or more gases and a second flow path around the hollow fibers for a flow of cell culture media and/or cells, preferably wherein the gas transfer module is located outside of the bioreactor , more preferred wherein the plurality of hollow fibers provide a flow path for culture media and cells to travel through spaces separating the hollow fibers, most preferred wherein the spaces are homogenous or heterogenous.

5. The method of claim 4, wherein the spaces are of sufficient size to allow passage of a cell without causing shear forces on the cell, preferably wherein the spaces comprise a distance of 15 µm to 2000 µm, more preferred wherein the spaces comprise a distance 15-30 µm, 20-40 µm, 30-60 µm, 40-80 µm, 60-120 µm, 80-160 µm, 100-200 µm, 150-300 µm, 200-400 µm, 200-500 µm, 200-600 µm, 200-700 µm, 200-800 µm, 200-900 µm, 200-1000 µm, or 500-2000 µm, or a combination thereof.

6. The method claim 4, wherein the flow of cell culture media and/or cells comprises tangential, axial flow or a combination thereof and/or wherein the flow of the cell culture media and/or cells is at a rate that is sufficient to maintain culture homogeneity

without causing shear forces on the cells.

7. The method of one or more of claims 1 to 7, wherein the gas is air, carbon dioxide, oxygen, and/or nitrogen, or a mixture thereof.

8. The method of one or more of claims 1 to 8, wherein the bioreactor comprises a cell density of 20 x 10^6 cells/ml, 30 x 10^6 cells/ml, 40 x 10^6 cells/ml, 50 x 10^6 cells/ml, 60 x 10^6 cells/ml, 70 x 10^6 cells/ml, 80 x 10^6 cells/ml, 90 x 10^6 cells/ml, 100 x 10^6 cells/ml, 110 x 10^6 cells/ml, 120 x 10^6 cells/ml, 130 x 10^6 cells/ml, 140 x 10^6 cells/ml, 150 x 10^6 cells/ml, 160 x 10^6 cells/ml, 170 x 10^6 cells/ml, or 180 x 10^6 cells/ml.

9. The method one or more of claims 1 to 9, wherein the method avoids production of foam.

10. The method of one or more of claims 1 to 10, wherein the bioreactor comprises no headspace or substantially no headspace.

11. The method of one or more of claims 1 to 11, wherein the method requires no anti-foaming agent during cell culture.

12. The method of claim 3, wherein the bioreactor comprises two or more gas transfer modules, preferably wherein the two or more gas transfer modules provide mass transfer of different gases comprising air, oxygen, carbon dioxide, or nitrogen gas.

13. A bioreactor system for high-density cell culture comprising a bioreactor vessel for growing cells in cell culture media and a liquid flow path in fluid communication with the bioreactor vessel, wherein the liquid flow path forms a circuit exterior to the bioreactor vessel for translocating cell culture media through a first and a second membrane gas transfer module.

14. The bioreactor system of claim 13, wherein the first membrane gas transfer module is for adding oxygen to the cell culture media, preferably wherein the first membrane gas transfer module comprises a oxygen flow path and a cell culture medium flow path,

and/wherein the gas flow path and cell culture flow path are separated by a gas-permeable membrane or further comprising an oxygen sensor that regulates the level of oxygen introduced into the cell culture media through the first membrane gas transfer module.

15. The bioreactor system of claim 13 or 14, wherein the second membrane gas transfer module is for stripping carbon dioxide from the cell culture media, preferably wherein the first membrane gas transfer module comprises an air/carbon dioxide flow path and a cell culture medium flow path, and/or wherein the air/carbon dioxide flow path and cell culture flow path are separated by a gas-permeable membrane or further comprising a pH sensor that regulates the level of carbon dioxide introduced into the cell culture media through the second membrane gas transfer module.

16. The bioreactor system of one or more of claims 13 to 15, wherein the liquid flow path that forms a circuit further comprises one or more additional elements, preferably wherein the one or more additional elements is a cell harvesting filter and/or wherein the one or more additional elements is a perfusion pump.

17. The bioreactor system of one or more of claims 13 to 16, further comprising a source of oxygen or further comprising a source of an air/carbon dioxide mixture.

18. The bioreactor system of one or more of claims 13 to 17, wherein the cells of the high-density cell culture are at a density of 20 x 10^6 cells/ml, 30 x 10^6 cells/ml, 40 x 10^6 cells/ml, 50 x 10^6 cells/ml, 60 x 10^6 cells/ml, 70 x 10^6 cells/ml, 80 x 10^6 cells/ml, 90 x 10^6 cells/ml, 100 x 10^6 cells/ml, 110 x 10^6 cells/ml, 120 x 10^6 cells/ml, 130 x 10^6 cells/ml, 140 x 10^6 cells/ml, 150 x 10^6 cells/ml, 160 x 10^6 cells/ml, 170 x 10^6 cells/ml, or 180 x 10^6 cells/ml.

19. The bioreactor system of one or more of claims 13 to 18, wherein the first and second membrane gas transfer modules add and/or remove gasses to/from the cell culture medium without forming bubbles.