Trade-off analysis of phase separation techniques for advanced life support systems in space

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Abstract

Phase separation in multiphase flows in space systems is a challenging task due to the absence of buoyancy. Several phase separation approaches have been presented in the last years given the important role that systems containing multiphase flows will play in future space missions. We present a review of these techniques and a trade-off analysis for their application in life support systems and, in particular, in the MELiSSA (Micro Ecological Life Support System Alternative) photosynthesis bioreactor. The candidate approaches are evaluated, both quantitatively and qualitatively, according to the defined requirements and criteria. The outcome of the trade-off analysis shows passive static and acoustic techniques as the most recommended methods to carry out phase separation in the considered bioreactor.

Keywords: Phase separation, Life support systems, Microgravity, MELiSSA, Bioreactor

1. Introduction

The space sector is increasingly focusing on long-term human missions that require the design and development of reliable advanced life support systems (LSS) able to efficiently work in microgravity conditions for extended periods of time. The functions of LSS correspond to the four basic needs for humans: breathe (atmosphere management, *i.e.* oxygen generation), drink (water management, *i.e.* water recovery), eat (food supply) and waste management. Depending on the mission duration, supplying all food, oxygen, and water from Earth can result in a tremendous effort in terms of mass and costs. Therefore, LSS have to be autonomous and regenerative [1, 2, 3]. The required autonomy means that the system must ensure the capability of both recycling wastes

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(air, liquid and solid waste) and producing food, potable water and oxygen. Food production with a suitable nutritional value for human beings can only be achieved by means of biological systems and living organisms (bacteria, higher plants, animals, etc.). In this perspective, regenerative means that these biological compartments must interact with the global system by contributing to the recycling functions, such as air revitalization (*i.e.* photosynthetic activity), water treatment and waste management, being as close as possible to a perfect closed-loop system. The most important element needed by a crew in space is oxygen, essential for breathing. In past human spaceflights, oxygen has been brought to space from Earth in tanks or produced through water electrolysis onboard. The latter technology is still used today, in the Russian Elektron and in the American Oxygen Generation Assembly (OGA).

One of the life support technologies currently in development is the Micro Ecological Life Support System Alternative (MELiSSA) of the European Space Agency (ESA). The driving element of the experiment consists in producing oxygen and edible biomass from wastes (*e.g.* high plants wastes, feces, urine, etc.), carbon dioxide and minerals with the use of light as a source of energy for photosynthesis [1, 2, 3]. One of MELiSSA main functions is to produce oxygen while eliminating the carbon dioxide. The task is achieved via photosynthesis using high plants or a photobioreactor. The photobioreactor is filled with a culture medium mainly composed of water and nutrients to maintain the growth of *Limnospira indica* cells (commonly known as *Spirulina platensis*). In the reactor, the CO_2 contained in injected bubbles is transferred to the liquid, where photosynthesis takes place generating O_2, which is transferred to the bubbles that will exit the bioreactor enriched in oxygen. In ground conditions, air bubbles enriched with CO_2 are injected at the bottom of the reactor and rise through the culture medium until they exit at the upper part. The size and distribution of the bubbles, gas flow-rate injected in the bioreactor, and mixing conditions dictate the mass transfer velocity between gas and liquid phases, which is a dominant factor determining the efficiency of the photosynthesis reactor.

Gravity on Earth strongly affects fluids behavior in several ways such as driving their motion, shaping phase boundaries, and compressing gases. In microgravity conditions, the effects of the gravity-driven processes are eliminated due to the absence of buoyancy. Therefore, forces and phenomena that are usually masked on Earth by gravity, *e.g.* surface tension, become relevant in space. In particular, a reduced gravity level can cause asymmetric two-phase flows and no shearing (bubbles not rising relatively to the liquid), which lead to a co-flow of gas and liquid. Consequently, a mixed volume of liquid and gas migrate only under the effect of surface tension, together with any external forces (electromagnetic, acoustic, impulsive-thrust, etc.) that may be present. Thus, liquid and bubbles would remain together in the MELiSSA bioreactor in space.

Multiphase flows are present in several systems in a plethora of space applications such as propulsion, thermal control, In-Situ Resource Utilization (ISRU), and Environmental Control and Life Support Systems (ECLSS). Multiphase mixtures of gas and liquid (and/or solid) can be produced in the flow by means of physico-chemical processes such as boiling or degasification. Multiphase flows in space environment must be well understood in order to design efficient technologies (*e.g.* condensers, evaporators, water processing devices). In particular, the mixing of phases needs to be addressed when gas-liquid phase separation is required in components of a system designed to work in one phase mode (*e.g.* centrifugal pumps, catalytic packed beds, bioreactors). The effects of a low gravity environment on LSS must be properly exploited so that the most appropriate phase separation technology can be selected according to the requirements of the system in which it will operate.

In order to ensure reliability and performance of a technology, often an active design approach is required, particularly for systems where contamination and variability of use can lead to poor, highly variable, or entirely unknown fluid conditions [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. For example, LSS employing centrifugal separators for urine, humidity condensate separations, and space suit liquid separation [7]. Although current active phase separators for LSS in space could satisfactorily achieve the goals in the MELiSSA photobioreactor for oxygen production, their weight and intrusiveness are not negligible drawbacks (*e.g.* centrifugal pumps or passive cyclonic separators) [1, 2, 3]. Extra-sized or heavy phase separators may require specific integration with the reactor or structural modifications, increasing its cost. Intrusiveness can be an issue because the chemical and bio compositions of the fluid medium are designed and controlled with respect to the oxygen generation performance. The reactor performance is a key element and the addition of substances to the fluid can damagingly change chemical parameters and/or interfere with the bio-functioning of the Spirulina cells. These cells are fragile and can be easily damaged by unnecessary mechanical motions or chemical contamination. In this context, a comparative analysis of existing and new phase separation techniques find its roots in the need of developing a light and low-intrusive technology able to deal with large biological LSS.

We present a trade-off analysis of phase separation techniques for the separation/extraction of oxygen from a fluid in microgravity conditions, particularly applied to the MELiSSA (compartment IVa, the photobioreactor with *Limnospira indica* cells). The requirements for the system are presented in Section 2. Section 3 contains a review of the state of the art of phase separation techniques for space applications. A trade-off analysis of the identified approaches for oxygen extraction in the MELiSSA photobioreactor is presented in Section 4. Results of the analysis are discussed in Section 5. Conclusions are presented in Section 6.

2. Requirements for a phase separator in space

One of the main challenges in advanced LSS such as the MELiSSA photobioreactor is the extraction of oxygen dissolved in fluids in weightlessness. The fluid can be water, in the case of water electrolysis, or a culture medium (nutrient solution with microorganisms), in the case of photobioreactors. The present study focuses in the MELiSSA photosynthesis reactor, which is constrained by physical processes (hydrodynamics, mixing, thermal control, sterilization, etc.) as well as environmental characteristics (reduced gravity, mass, energy consumption, etc.). In this bioreactor, CO_2 from injected bubbles is dissolved in the liquid, which at the same time desorbs O_2 produced by the bacteria.

Physico-chemical and biological processes in gas exchange are influenced by the functioning of the photobioreactor and the dynamics of the multiphase solution (bubbles, culture medium and cells) in space. Cells, which have to be kept alive, are more susceptible than inorganic molecules to external stresses (vibration, shear stress, pH changes, etc.), which can easily kill them. In addition, organic and living compounds significantly increase the probability of bio-fouling, which is detrimental to the gas-liquid interface.

In order to carry out a trade-off analysis of phase separation techniques, a set of requirements must be established. The primary system-level requirements for the application of the technique in the MELiSSA bioreactor are:

1. Operating conditions: pH at the 8.5-9.6 range, temperature at 36°C, and pressure below 0.2 atm [1, 2, 3].
2. Minimum mass and power consumption.
3. Chemical and bio-compatibility to prevent damage to cells.
4. Cleaning, sterilization capabilities, structural-compatibility and contamination prevention (e.g. bio-fouling and bio-erosion).
5. Minimum liquid loss.
6. Safety and reliability.
7. Risk evaluation.
8. Long-term missions.
9. Performance: transfer of at least 7 mmol/h of oxygen from the liquid to the cabin, taking all the necessary precautions to avoid microbiological contamination.

The most limiting requirements for a phase separation technology are system mass, performance, and a safe interaction with the cells in free suspension in the fluid in the reactor. Cells could be damaged, for example, by a centrifugal motion of the culture medium.

3. Phase separation techniques

For each technique considered in this study, all the necessary data (physical models, efficiency, mass, components datasheet, power consumption, etc.) were gathered in order to perform the trade-off analysis. Various approaches employing different functioning principles can be considered for phase separation in a reduced gravity environment. Bubble trap techniques, which allow physical separation of gas contained in a liquid, have been traditionally used. In order to increase the performance of current systems, many approaches have been proposed, some of which were demonstrated in space. They range mainly from microchannels and microporous membranes to ultrasounds, centrifugal/cyclonic separators and other active techniques (*e.g.* thrusters, magnets, electric pumps).

Phase separators can be classified into two main categories: passive and active. Passive separators refer to all the techniques that can afford the phase separation without the need of moving mechanical components or power input. Active phase separation requires power input and/or moving components. Phase separators can also be classified according to their functioning principle, static or rotary. Rotary techniques rely on generating artificial body forces by rotating equipment. Static techniques are based on other forces, such as external force, or wetting and capillary force, or in the generation of vortex flows without moving parts.

Hereafter, the main phase separation techniques are introduced, being categorized as Capillary (passive-static), Rotary (passive or active) or Active (static). For each approach, the functioning principles, performance, advantages and drawbacks are highlighted. Table 1 summarizes the techniques presented in the following sections. The quantitative and qualitative evaluation of these methods and their comparison is the basis of the trade-off analysis.

Table 1: Phase separation techniques.

Section	Category	Principle	Technique	References
3.1.1	Passive-static	Capillarity	Inertial	[4]
3.1.2	Passive-static	Capillarity	Pure capillary	[5, 6, 7]
3.1.3	Passive-static	Capillarity	Porous media and membranes	[8, 9, 10, 11, 12, 13, 14, 15, 16]
3.2.1	Rotary-active	Mechanical spinning	Centrifuges	[17]
3.2.2	Rotary-passive	Flow momentum	FVS/Cyclonic	[18, 19, 20, 21]
3.3.1	Active-static	Rocket firing	Thrusters	[22, 23]
3.3.2	Active-static	Electric force	EHD	[24]
3.3.3	Active-static	Magnetic force	Magnets	[25]
3.3.4	Active-static	Acoustic force	Acoustic	[26, 27, 28, 29, 30, 31, 32, 33, 34]

3.1. Capillary techniques

Passive-static phase separation techniques typically rely on capillary forces to achieve the desired goal. The employed methods include wicking, membranes, porous plug and hydrophobic/hydrophilic meshes, flow design with sudden direction changes or elbows, or a combination of all of them.

Capillary forces are present in fluid interfaces. All systems containing fluids, even those designed with non-capillary solutions, should consider capillarity to enhance the reliability of the overall system. In this way, the system possesses built-in redundancy and it may function in the event of primary system failure. Such capillary solutions do not incur in power draw penalties, nor do they always incur in mass penalties. Hence, even in the design of an active separator, which is usually more reliable and performant, and where contamination and variability of use can lead to wetting conditions that are poor, highly variable, or entirely unknown, capillary forces will always have to be taken into account, since they are often predominant in microgravity. This might include any combination of thermo-, electro-, magneto-, acoustic-, solute-, or 'other-' capillarity. Therefore, by means of a careful selection of components geometry, it is possible to obtain passive phase separation, collection, and control operations throughout the system, even if the system is not considering capillarity as the main driving force for the flow or flow separation function.

Capillary approaches are standard for the control of liquids in different spacecraft systems (*e.g.* propellant in cryogenic tanks or liquid flow in thermal control systems). These systems exploit container geometry and fluid properties (primarily wetting) to passively transport fluids to the desired positions. For example, a simple interior corner (edge) in a fuel tank between the tank wall and a planar vane can act as a passive guide to transport large quantities of liquid along it by capillarity. Hence, the shape of the container can serve as a pumping mechanism to make sure that the liquid and gas are where they ought to be.

Although capillary techniques are expected to be essentially passive, low mass, and potentially highly reliable, they are only well established if the wetting conditions are known and favorable. Thus, they significantly depend on flow regimes (annular, slug, bubbly, etc.) and on the wetting conditions and variability (contact angle hysteresis).

The capillary techniques considered in this study can be divided into inertial separators (elbows and impingement separators) [4], and purely capillary separators [5, 6, 7]. Capillary separators (microchannels) can rely on porous media [8], hydrophilic/hydrophobic screens/membranes [9, 10, 11, 12, 13, 14, 15, 16], or a combination of them. These membranous systems can also be employed as standalone separators.

3.1.1. Inertial separators

Jenson *et al.* carried out the design of a passive phase separator in a bubbly flow using conduit geometry [4]. The designed wedge geometry provides a

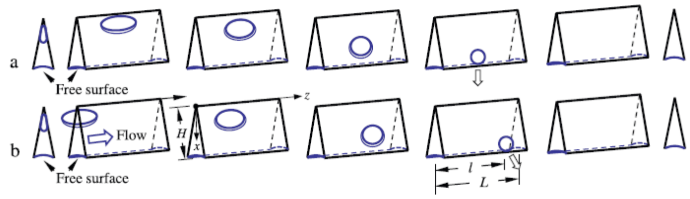


Figure 1: Time series of capillary-dominated bubble migration in an acute wedge-sectioned conduit of length L. a) zero base flow, b) non-zero base flow [4].

passive capillary means to separate gas bubbles from a liquid flow, specifically for applications in low gravity environments. In this device, bubbles passively migrate towards the free surface, where they coalesce and leave the flow. Authors analyzed the mechanisms for low gravity bubble migration in a wedge, considering the case of only influence of capillary forces (zero base flow) and the case of additional liquid driven through the conduit by a pump ('non-zero' base state liquid flow). The functioning principle of the tecnhique is represented by the micro-gravity motion of a bubble in a conduit geometry, which is depicted in Fig. 1 (a) zero base flow, and b) non-zero base flow). Several tests were carried out in a drop tower, highlighting the relations between geometry of the bubble, wedge-angle and flow rates. Experiments were also carried out in the NASA Capillary Channel Flow (CCF) in the International Space Station (ISS). From the tests in both microgravity platforms, authors concluded that depending on the gas and liquid flow rates, characteristic bubble volume, and vertex-included angle, the migrating bubbles can collect and coalesce in the widest region of the conduit section. In the case of the presence of a free surface, bubbles may escape through it achieving a desirable 100% passive separation function. Several considerations of the study can serve as a guide for the design process when exploiting laminar flows along acute polygonal conduits (*i.e.* open asymmetric wedge channel, or rather inertial separators).

3.1.2. Pure capillary separators

The performance of a capillary intake device (CID) was studied by Kichatov *et al.* [5]. The CID is intended as a system of extraction of liquid propellant in rocket propulsion, in the case of re-ignition and operation in microgravity conditions. Fig. 2 shows a scheme of a CID. The main element of a CID is a capillary phase separator (CPS) that divides the tank volume into the main space containing liquid and gas, and the CID space filled with only liquid. The liquid from the main space may reach the outlet opening only after passing through the CPS pores into the CID space. Therefore, the liquid pressure in this space is lower than that of pressurization gas in the main space. A pressure difference impeding the passage of gas through the gauze screen is realized in every region of the surface.

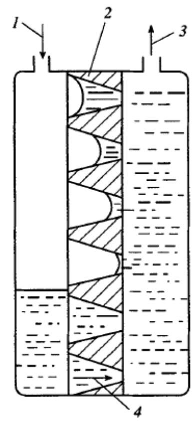


Figure 2: Capillary intake device: (1) gas inlet, (2) CPS (phase-separating screen), (3) liquid outlet, (4) direction of the liquid through the CPS [5].

A technology consisting in a microchannel phase separator able to support endeavors for ISRU in lunar or Martian environment was presented by Ward *et al.* [6]. The fundamental approach for the microchannel phase separation technology consists in the use of capillary, surface, and hydrodynamic forces to collect one of the phases into specific flow regions while excluding the other. In essence, these forces are used to remove or recover a dispersed fluid phase from a second immiscible phase. The same principles apply to droplets dispersed in a liquid (emulsion), gas dispersed in a liquid (bubbles), or liquid dispersed in a gas (aerosol). Phase separation is accomplished using combinations of capture, wicking, and pore throat structures within the microchannels. The experimental apparatus consists in a gas flow channel and an adjacent liquid channel (Fig. 3). The gas-liquid mixture enters the device and flows through the region containing the capture structure. Capillary, surface, and hydrodynamic forces make the liquid phase to come into contact and preferentially sorbs into the adjacent wicking/pore throat structure. This structure provides a path for the liquid to flow to an outlet while precluding gas intrusion. The porous structure is characterized by high permeability to provide flow capacity to the outlet. The gas phase exits from a separate outlet. Tests were carried out in the single liquid microchannel, while the gas channel was open and did not contain the capture structure. All experiments were performed with air as the gas phase. Four different liquids were used in order to vary the fluid properties and the viscosity ratio (water, 4 cP and 14 cP glycerin/water mixtures, and decane). The most important factors governing performance are related to the design of the pore throat structure, in terms of flow capacity. Phase separation was lost when the liquid flow rate reached about 40-60% of the pore throat capacity. However, breakthrough could still occur either with a small (10%) or a large (90%) utilization of pore throat capacity, depending on gas-liquid-ratio, Reynolds numbers and Suratman number. Breakthrough of liquid to the gas

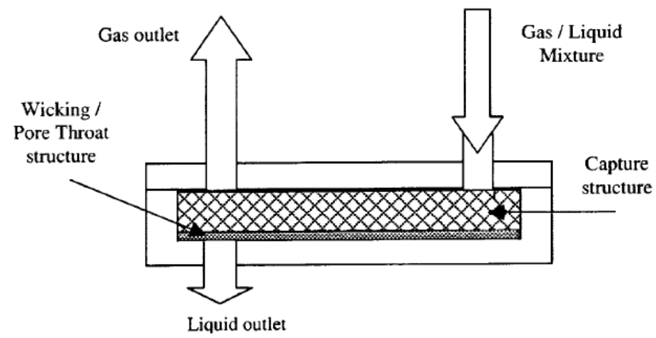


Figure 3: Single-microchannel phase separator with a wicking structure to capture the liquid and an optional capture structure in the gas channels [6].

outlet occurs in the same flow region where a transition occurs between annular and slug flow in a pipe in microgravity.

Weislogel *et al.* considered a purely capillary separator for a urine collection system [7]. Fig. 4 shows the concept of this phase separator. The design deals with the most limiting worst-case scenarios in terms of operational wetting conditions. The objective is to ensure that the ultimate capillary solution would be one capable of handling all flow regimes, wetting conditions and able to passively recover from significant excursions in background acceleration level. Different tests were executed aboard the NASA low gravity aircraft. The experimental conditions were selected to demonstrate the capabilities of the device to collect highly variable (partially) wetting liquids out of a two-phase stream for subsequent processing. Tests were specified for transient and steady operation for a variety of initial conditions, flow rates, and flow rate ratios. In one limiting worst-case scenario of poor wetting and large contact angle hysteresis, the liquid was collected by non-capillary means such as centrifugal and/or air drag forces, but held together by capillary forces. In the second limiting worst-case scenario of perfect wetting, low volume liquid films were produced and driven downstream by the airflow.

3.1.3. Porous media and membranes

Since the dawn of space exploration, membranes have been extensively used for phase separation aboard spacecrafts, particularly for thermal control systems and ECLSS. The different kinds of existing membranes are characterized by their structure, shape and material composition. Space suitable membranes take advantage of the porous plug effect in order to achieve gas-liquid phase separation. Indeed, hydrophobic microporous membranes are always used to form a permeable barrier between liquid and gas, which permits the mass transfer between the two phases without dispersing one phase into the other. The two

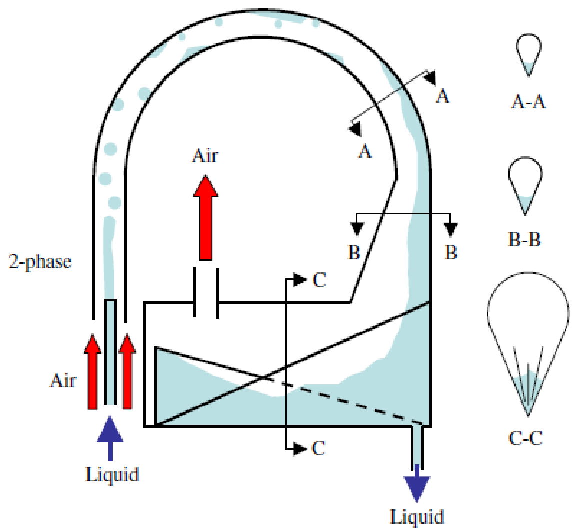


Figure 4: Phase separator concept for urine collection system. A-A: flow guided rivulet section, B-B: diffuser section, C-C: containment section [7].

phases always flow in parallel fibers (hollow fiber modules membranes, HFM) and the gas preferentially fills the hydrophobic pores meeting the liquid at the opposite side of the membrane.

Hasan *et al.* developed the condensing heat exchangers (CHX) technique, which uses a cooled porous substrate as the condensing surface, providing simultaneously heat removal and liquid-gas separation into a single unit (Fig. 5) [8]. The system is capable of operating under varying gravitational environments, including microgravity. Authors performed a study and design of the porous plug geometry and characteristics in order to achieve the desired phase separation. The functioning principle of the technique is based on condensate retention in the porous substrate and water extraction (by applying suction) once the saturation of the pores reaches a certain level. The porous substrate contains cooling copper tubes through which chilled water is circulated. Condensation of moist air occurs inside and over the porous substrate when cooled. The condensate is absorbed by capillarity and the embedded porous tubes selectively remove the accumulated water within the porous plate. Air penetration into the porous tubes is avoided by selecting tubes with a high bubble pressure relative to the porous substrate. The hydrodynamics of air/water flow in porous media is reasonably well understood and the physical processes of both condensate retention in the porous substrate and water extraction from unsaturated porous media are provided in the paper. Preliminary bench-top experiments demonstrated the feasibility of this concept.

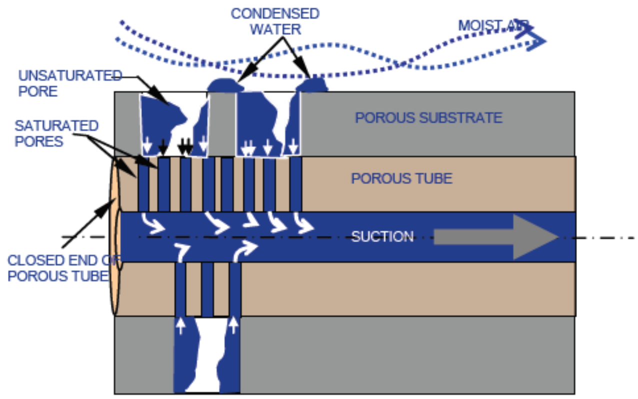


Figure 5: Porous substrate and condensate removal tubes with different pore sizes (not scaled) [8].

Noyes *et al.* analyzed a microporous hydrophobic HFM for gas-liquid phase separation in microgravity [9]. Fig. 6 shows a sketch of this phase separator. The functioning is based on keeping a higher pressure in the liquid water side than in the gas side, so that water (or any aqueous solution) does not enter in the membrane pores, and also preventing gas from mixing with the bulk of the liquid. All the specific requirements that a microporous hydrophobic HFM must meet to properly carry out its functions, in terms of materials, geometry and structure were provided in [9]. Experiments were carried out in order to demonstrate the gas-liquid phase separation, as well as the removal of dissolved gas (de-bubbler/degasser) and the transport of water vapor, in different orientations relative to gravity (vertical downward and upward, horizontal and 45° upward). Experiments showed that gas-liquid mass transfer operations could be implemented in passive devices that create a high phase-contact area in a small volume, independently of gravity level, liquid settling and gas buoyancy effects. In addition, the behavior of the HFM was found to be independent of the type of gas (O_2, N_2 or air) and flow rate.

Scovazzo and co-workers considered the membranous phase separation in ECLSS for space applications [10, 11]. The design and test of a membrane for dehumidification of a plant growth system in low gravity conditions was carried out in [10]. This kind of system requires the generation of no free-liquid condensate and the recovery of water for reuse. Different hydrophilic membranes for humidity control (hollow fiber cellulose ester membranes, metal membranes and ceramic membranes) were compared and evaluated. Fig. 7 shows schemes of these membranes. The membrane performance is mainly determined by its properties, in particular, by the ratio of fluid surface area to membrane material area (membrane porosity).The membrane acts as a barrier between the humid

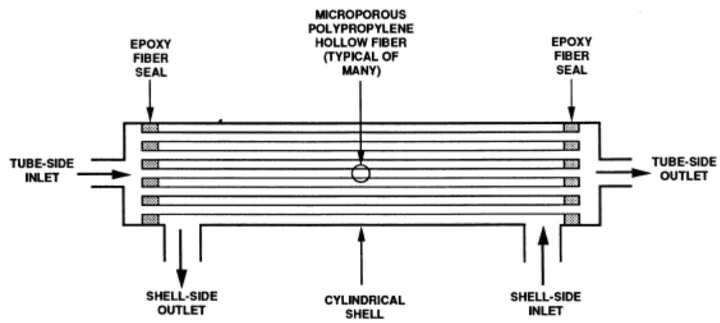


Figure 6: Microporous Hydrophobic HFM (Hollow Fiber Modules) design [9].

air phase and a liquid-coolant water phase. The dehumidification and humidity control processes were tested in a plant growth chamber using the different types of membranes. The results obtained lead to the identification of several critical factors for the selection of a hydrophilic membrane material.

Numerical models and similarity criteria were developed for two-phase flows in membranes and porous media in irrigation systems in microgravity conditions by Scovazzo *et al.* [11]. Key design factors were identified for these systems: porous media properties, applied water potential, and the ratio of inner to outer radius for cylindrical and spherical porous media systems. In addition, sets of similarity criteria to compare different microgravity experiments or to scale-up during system design were introduced.

Cogne *et al.* carried out a study on the design, operation, and modeling of a membrane photobioreactor in space conditions [12]. Different porous membranes for gas-liquid separation were considered in the work. In the long-term experiments and ground tests described, the oxygen was successfully separated using a 0.2 µm Poly-Tetra-Fluoro-Ethylene (PTFE) porous membrane as gas separator. The thickness of the membrane was 57 µm, and the exchange surface area was 19.6 cm^2. The main drawback of the technique was the high permeability to water vapor of the porous structure, which may cause volume variations in the liquid phase and the appearance of gas bubbles on the liquid side, disturbing the mixing quality in microgravity.

Soreanu *et al.* considered a non-porous hollow fiber gas permeable (GP) membrane biological reactor and evaluated the oxygen transfer efficiency [13]. Fig. 8 shows the reactor, highlighting the different components. GP membranes are characterized by high gas transfer efficiency and precise control of delivery rates. The performance of the GP membranes was compared to the performance of coarse and fine bubble diffusers, under identical reactor conditions. GP membranes showed the best oxygen transfer performance and the lowest energy requirements.

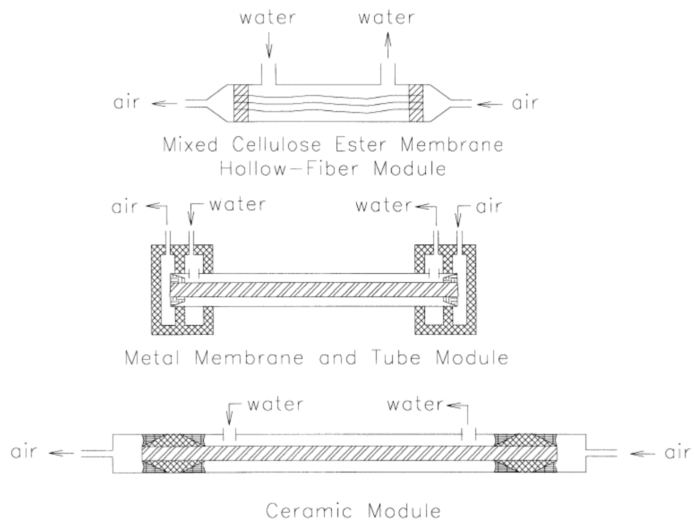


Figure 7: Types of membranes [10].

Gas–liquid transfer in microgravity conditions was characterized by Farge *et al.* employing a particular microporous PTFE hollow fiber membrane contactor (HFMC) [14]. An accurate characterization of the mass transfer coefficient of CO_2 and O_2 in a photobioreactor was carried out. The employed experimental methods accurately characterize the gas–liquid mass transfer through membranes in microgravity conditions. Results demonstrated that membranes could be efficiently used in reduced gravity conditions to exchange CO_2 and O_2 in photobioreactors and regenerate atmosphere in closed systems.

Heo *et al.* described a technique for separation of dissolved gases from water, applied to a portable underwater breathing device by means of a pipe type of HFM [15]. The performed experiments analyzed the separation characteristics in the test of a battery-driven vacuum pump underwater. Oxygen was separated from water in a percentage ranging from 30% to 40%, depending on the water flow rate.

Su *et al.* recently tested a novel tri-bore Poly-Vinyli-Dene Fluoride (PVDF) hollow fiber membrane for the control of dissolved oxygen in aquaculture water [16]. Ground experiments with distilled water showed a dissolved oxygen removal efficiency generally ranging between 68% and 90% depending on the flow rate, with a maximum of 97.5% when water flow rate was 100 ml/min. The deoxygenation efficiency decreased to 87.3% when applied to aquaculture water. The tri-bore hollow fiber membranes performance improved when two membranes were connected in series.

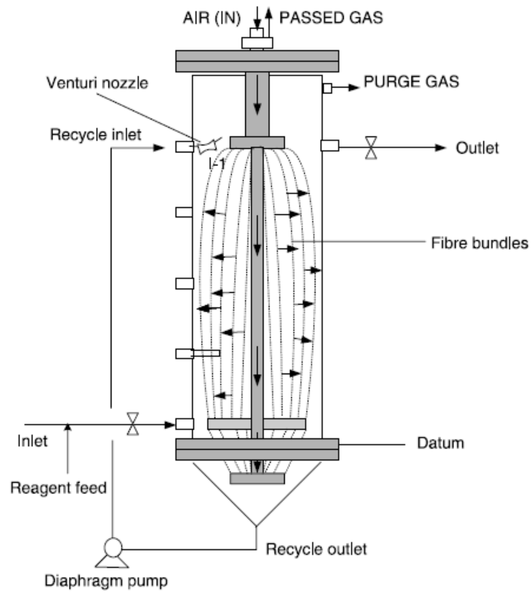


Figure 8: Membrane biological reactor [13].

3.2. Rotary techniques

Rotary approaches provide phase separation by means of the generation of artificial forces (centrifugal/centripetal) either by rotating equipment (active, *i.e.* centrifuges) [17] or by vortex flows (passive, *i.e.* cyclonic separators) [18, 19, 20, 21]. Active and passive rotary separators differ from each other by the source of the applied centrifugal force.

3.2.1. Centrifuges

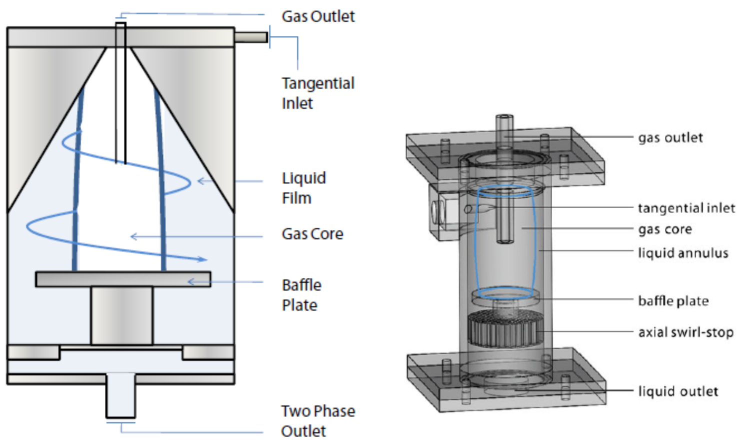
Active devices take advantage of mechanical spinning to achieve their goal. Motor-driven centrifugal separators are an example of active rotary separators that rely on rotation to develop a centrifugal acceleration to separate phases based on their density difference. Despite being very efficient, active separators require a significant amount of power, rotating machinery (*e.g.* shaft, bearings, a motor or thrusters), and periodic maintenance. The needs of the new space sector require lightweight systems with the lowest possible power consumption. Hence, heavy motor-centrifugal separators are employed only when performance is the most critical requirement to the detriment of system weight. These phase separators have been used in the ancestor LSS for space applications, such as the Urine Processor Assemble (UPA) or the Water Processor Assemble (WPA) aboard the International Space Station. Centrifuges are applied in many disciplines in both life and physical sciences [17].

3.2.2. Cyclonic separators

Phase separation in passive rotary separators is achieved by inducing a flow rotation in a fixed tank by means of an eccentric injection of the liquid-gas mixture (Free Vortex Separator or FVS), or by designing swirling and vortical flow paths in pumped loops. These separators have no moving mechanical parts, require low power, and have been extensively investigated thank to their simplicity and dependability [18, 19, 20, 21].

Cyclonic separators provide gas-liquid separation by swirling the multiphase flow [18, 19]. Fig. 9 shows scehems of two cyclonic separators. Gas accumulates along the axis of the vortex (as the denser liquid is forced to the walls), allowing segregated extraction of each phase. Passive cyclonic separators only use the inertia of the incoming flow to accomplish this task. The functioning principle is based on the generation of a swirling flow by tangential injection of the multiphase fluid stream into the separator device. This eccentric injection thereby creates a buoyancy-like separation action via the pressure gradient that arises to maintain the necessary centripetal acceleration of the fluids as they swirl within the device housing. A gas core forms along the axis of the device (in between the cylinder top and the baffle plate), and the separated phases are removed via their respective outlets. Hoyt *et al.* [18, 19] combined experimental and numerical analysis in order to quantitatively describe the steady and dynamic operation of these separators. Computational and analytical techniques were successfully validated for future microgravity separator designs by comparison with experimental results, and a 1-g database for comparison was created. Tests were executed on ground in a gravity-independent manner with the separator longitudinal axis perpendicular to Earth gravity. The main advantage of cyclonic separators is their static passivity combined with long duration operability. Indeed, compared to the other techniques considered here, problems limiting the operational lifespan, such as clogging of membranes, are not present. This advantage arises because the approach employs the inertia of the multiphase flow to provide the desired phase separation.

Xu *et al.* carried out an analysis of dissolved carbon dioxide separation from water employing an inner cone hydro-cyclone, which consists of a cylinder containing two inner cones (Fig. 10) [20]. The flow is injected tangentially and a strong swirling motion is developed within the inner cone. Dense fluid moves close to the wall, while bubbles move along the center line (air core). De-aerated liquid escapes the device through two tangential liquid-outlets, while gas exits through two axial gas outlets. Results showed that an increase of the inlet mass flow increase the separation efficiency up to a threshold after which increasing the inlet mass flow decreases the separation efficiency.



(a) (b)

Figure 9: Cyclonic separators: a) [18], b) [19].

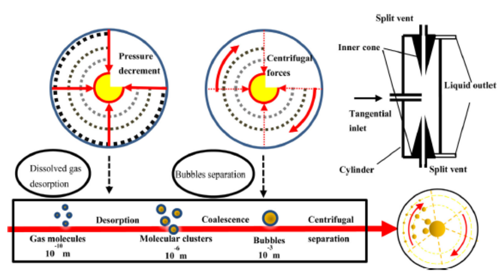
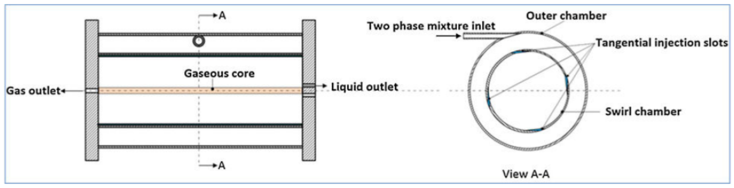
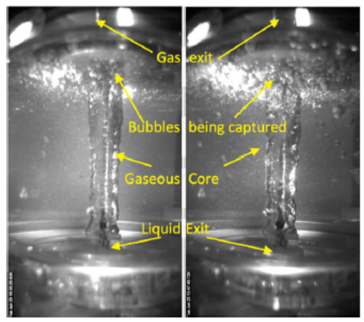


Figure 10: Inner cone hydrocyclone separator [20].



(a)



(b)

Figure 11: Swirl flow separator: a) Scheme, b) Zoom of the vortex core of the phase separator during the tests in microgravity (left: 8% void fraction, right: 31% void fraction) [21].

The main drawback of cyclonic separators is related to their dependence on the void fraction. The Cascade Cyclonic Separation Device (CSD-C), for instance, has an efficiency approaching 100% for mid-range void fractions (50 – 80% gas), but is not as efficient for lower void fraction [21]. In order to fill this gap and to address effectively the dependence on void fraction, the DynaSwirl® phase separator (a swirl-flow separator-cavitating-nozzle) was proposed in [21]. The system, which consists of two concentric cylinders, generates flow rotation with high circulation to induce cavitation at the center of the vortex at low flow rates. The swirling flow inside the inner cylinder is generated with wall tangential slots, which enable flow from the outer cylinder to the inner cylinder. Fig. 11a shows a scheme of the device. The microbubble growth and collection can be induced and controlled by changing the tangential velocity (and, consequently, the pressure on the axis). This device was integrated in the NASA breadboard test rack for ground and reduced gravity flight tests. Tests showed that the phase separator is capable of efficiently and reliably separate gas–liquid mixtures of high and low void fractions in a wide range of flow rates for space and Earth applications. Fig. 11b shows the vortex core of the phase separator in microgravity with different void fractions.

3.3. Active techniques

Static-active techniques can be used to achieve phase separation with the aid of external forces different to centrifugal. Artificial accelerations may be created by thruster/rocket firings [22, 23], or by by electric [24], magnetic [25], acoustic [26, 27, 28, 29, 30, 31, 32, 33, 34], or other external forces.

3.3.1. Thrusters

The rocket firing approach is mostly used for propellant management [22]. The gravitational force induced by the thrust allows the separation of the liquid-gas mixture. The liquid is resettled to the bottom of the tank and can be pumped to the engine. This kind of separator is hardly applicable to LSS since, particularly for bioreactors, rocket firing should be continuous. Hence, this method would be excessively expensive in terms of thruster fuel consumption.

Another approach based on thrusters that can generated phase separation is artificial gravity (AG). AG is the result of constant or partial rotation of the spacecraft started by means of thruster ignition [23]. The advantage of employing a constant AG in space is that the rotation, and consequently the thruster ignition, can be applied only once and the rotational motion would continue endlessly, barring external forces or perturbations. However, AG is more a characteristic of the hosting spacecraft and the environment rather than a technique to be integrated to the LSS considered in this study.

3.3.2. Electrohydrodynamic pumps

Feng *et al.* studied phase separation with a technique based on electric forces [24]. The application of this technique is particularly addressed to thermal management systems, since most refrigerants and cryogens used in these systems are dielectric liquids. Electrohydrodynamic (EHD) pumping shows its potential to actively control the flow distribution when employing dielectric liquids. The conduction pumping is based on the hetero-charge (the process of dissociation of the neutral electrolytic species and recombination of the generated ions) of the fluid layers in the proximity of the electrodes. This charge can be used to electrically drive the dielectric liquid and to effectively control the flow distribution among parallel pipelines. Fig. 12 shows the schematic design of a EHD conduction pump electrode. Ground tests successfully demonstrated the ability of the EHD conduction pump to drive and control the liquid flow distribution between two branch lines at various mass fluxes [24]. In addition, the corresponding consumed current remained below 100 µA. EHD pumps require dielectric behavior of the liquid, which can substantially affect the composition of the fluid in the bioreactor and its functioning, increasing the cost.

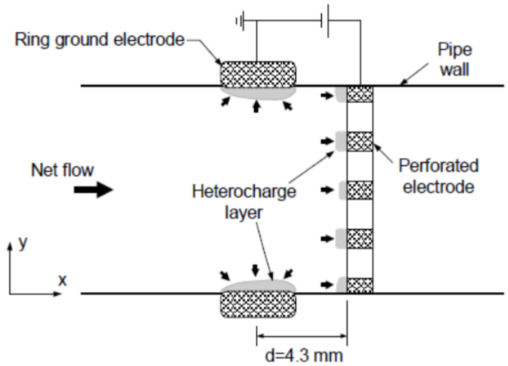


Figure 12: EHD conduction pump electrode [24].

3.3.3. Magnets

Phase separators relying on magnetic forces have been used for liquid propellant tanks in microgravity. One approach consists in using a colloidal suspension of magnetic particles in the liquid such that they are attracted by different magnets retaining the liquid itself in the tank, while permitting venting of the gas [25]. The colloidal suspension inevitably increases the complexity of preparation of the fluid to use. Fletcher *et al.* described a low gravity phase separator in a sub-critical cryogenic helium vessel, which takes advantage of the diamagnetic property of liquid helium [25]. This device was designed to separate vapor and liquid of a diamagnetic cryogen in microgravity to reduce venting of the liquid phase for a spectrometer to measure cosmic ray and like effects. By placing the gas outlet vent close to the superconducting magnet, diamagnetic liquid helium is repelled and only vapor helium is present at the gas outlet vent. In fact, this approach consists in repelling the liquid rather than attracting it. Liquid helium can be retained in the tank for long periods, extending the service life of the superconducting magnets for long duration experiments.

3.3.4. Acoustic transducers

Bubbles in a liquid can be controlled by means of acoustic waves generated by a piezoelectric transducer. The acoustic primary Bjerknes force makes bubbles larger/smaller than the resonant size to move to a node/antinode of a pressure standing wave [26]. If a pressure travelling wave is applied, bubbles are moved away from the acoustic wave generator. The secondary Bjerknes force corresponds to the acoustic force exerted by an acoustically excited bubble to a neighboring bubble.

Oeftering and Chato proposed the so-called "smart tank" (Fig. 13), a device that combines acoustic imaging with manipulation techniques allowing the system to both "see" as well as "act" on selected targets [27]. The system em-

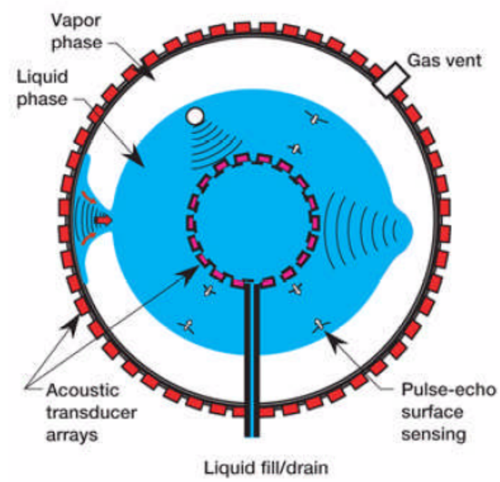


Figure 13: The "smart tank" [27].

ploys acoustic phased arrays to steer and focus the acoustic beams electronically, making it possible to operate on multiple targets as needed.

A study on the ultrasonic effects on solubility and mass transfer in gas-liquid systems was carried out by Laugier *et al.* [28]. Experiments were performed in a stainless steel ultrasonic autoclave reactor. The gas–liquid system chosen was nitrogen and deionized water. Results showed a very low impact on solubility (below 12%), while the gas-liquid mass transfer was greatly improved. The use of ultrasounds to enhance gas-liquid mass transfer was very efficient even in the absence of gas induction (*i.e.* gas agitation is not required). Authors concluded that ultrasound is a promising tool to enhance gas–liquid mass transfer even at high pressure and temperature, and in the absence of induced bubbles.

Manipulation of particle trajectories was addressed in microfluidics devices in [29, 30]. Orloff *et al.* controlled the trajectory of particles by changing the position of the acoustic nodes by means of a variation of the phase of the wave generated by a transducer [29]. Garcia-Sabaté *et al.* analyzed the interaction between particles in an acoustic field, obtaining values for the secondary Bjerknes force, which was found to be much smaller that the primary Bjerknes force [30].

Luo *et al.* provided an extensive review on the terrestrial applications of acoustic phase separation using ultrasonic standing waves [31]. Applications included biological materials, food processing, and petrochemical industry. The employed methods rely on static separation using multi-waves and flow separation using multi-waves, semi-wave or sweep frequency. The most appropriate

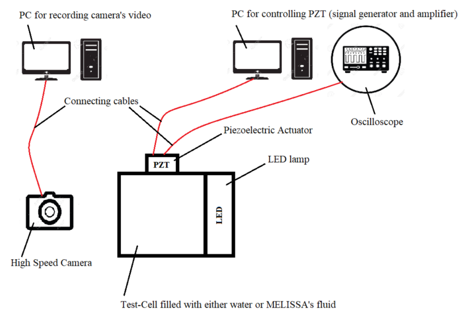


Figure 14: Experimental setup to test the acoustic approach with the MELiSSA photobioreactor fluid [34].

approach for each application depends on the separation principles and, consequently, on the type of particles considered in the system.

An acoustic technique for the management of vapor bubbles generated by boil-off in cryogenic fuel tanks in microgravity is currently under development [32, 33]. In this approach, bubbles generated at hot spots in the tank are detached by means of controlled acoustic waves and moved to colder regions where they condensate. An approach based on the obtained results so far has been used to show the feasibility of the acoustic technique for phase separation in the MELiSSA photobioreactor [34]. Fig. 14 shows the experimental setup employed with the photobioreactor fluid.

4. Trade-off analysis

The trade-off analysis can be carried out taking into account the phase separation techniques and the requirements for the LSS. A set of criteria for the analysis have to be defined based on the identified requirements of the system and the usual criteria for space systems [35, 36, 37]. Both quantitative and qualitative criteria are taken into account. Whenever quantitative data are available, techniques are classified according to the corresponding values. Otherwise, a qualitative analysis is performed on the characteristics of the technique. The following criteria have been identified for the trade-off analysis of phase separation techniques for an advanced LSS in space:

- Intrusiveness: chemical and bio-compatibility with the LSS, in particular the effect of the technique on the functioning of the system (specifically referring to requirement 3 in Section 2).
- Performance: phase separation level achieved, efficiency and dependability on the system, *i.e.* the relation between technique and application with respect to the flow condition and regime (referring to requirements 5 and 9).

- Applicability: ability of the technique to be applied to the LSS as it is (referring to requirement 4).
- Operational lifespan: expected duration of the component before repairs or replacement, considering the effect on maintenance and management of the technology (referring to requirement 8).
- Reliability and maintainability: level of security, redundancy and reaction to failure of the system (referring to requirements 6 and 7).
- Operational conditions: physical properties required by the technique and their effect on the considered application (referring to requirement 1).
- Power consumption: power required to achieve the desired phase separation (referring to requirement 2).
- TRL: Technology Readiness Level.
- Geometry and structure, including system mass and volume: effect on launch and transport (referring to requirement 2).
- Cost: cost of manufacturing, development, operation and maintenance.

A weighting factor is assigned to each criterion according to its relative importance in relation to the others. The weighting factor ranges between 0 (less determinant criteria) and 5 (mandatory criteria). The weighting factor of each criterion in this analysis is assigned with the aim at identifying the most suitable phase separation technique in the context of oxygen production in the specific LSS considered (MELiSSA photobioreactor) for long-term human missions. Different weighting factors could be associated to criteria in other LSS. The highest weighting factor in this analysis is assigned to applicability, intrusiveness, and performance, followed by lifespan, reliability and maintainability. Mid-range weighting factors are assigned to operational conditions, power consumption and TRL. Geometry and cost are considered the least determinant criteria.

All the techniques in Table 1 receive a score between 0 and 5 in each criterion, so that the highest score corresponds to the most suitable technique for that criterion. Table 2 shows the scale employed to score the techniques (intermediate values are assigned according to a linear scale). In the case of criteria without quantitative data (*e.g.* reliability, applicability), the score is assigned from the comparison between the considered techniques.

The total score for each technique is obtained from:

$$Total = \sum_i (score(i) \cdot weight(i)), \tag{1}$$

where i refers to each considered method. Eq. 1 is meant to give a fair and unbiased score to all the approaches. Table 3 summarizes the results of

Table 2: Trade-off criteria and score scale.

Criterion	Score	
	0	5
Intrusiveness	Not compatible with the application	Compatible with the application
Performance	10% phase separation	100% phase separation
Applicability	Technique not applicable to the system as it is	No modifications required to the application system
Operational lifespan	< 1 hour	> 1 year
Reliability and maintainability	Low level of reliability	High level of reliability
Operational conditions	Strong influence on physical parameters (T, P, pH)	No physical properties are modified (T, P, pH)
Power consumption	> 100 W	< 1 W
TRL	TRL 1	TRL 9
Geometry and structure	> 1 kg	< 1 g
Cost	Low	High

the trade-off analysis of the techniques reported in Table 1, taking into account the criteria in Table 2 and their weighting factor. Results are also graphically represented in Fig. 15 by means of spider charts comparing all the techniques (Fig. 15a), and the techniques by category (passive *vs.* active in Fig. 15b, and static *vs.* rotary in Fig. 15c). "W" followed by a number indicates the weight associated to the requirement in the analysis.

5. Discussion

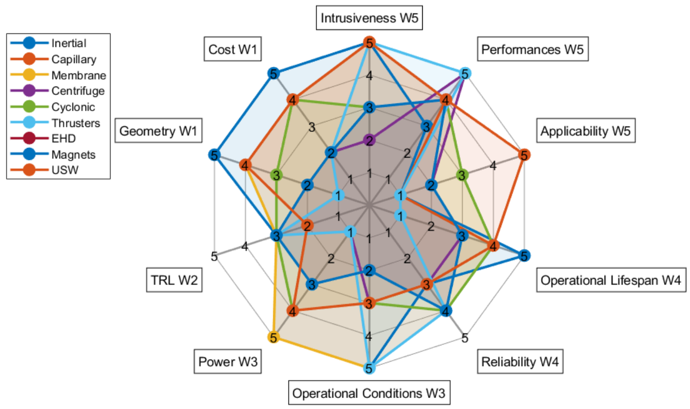
The trade-off analysis has been performed to compare phase separation techniques for their application in the MELiSSA photobioreactor. The considered approaches and criteria could still be valid for other LSS. However, criteria, weighting factor and score assigned to techniques might differ according to each application. Intrusiveness and applicability, for example, could be less important in other LSS than they are in the photosynthesis bioreactor.

The acoustic and passive static techniques achieve the highest score in the analysis. The rest of active static techniques and the rotary ones get a lower total score.

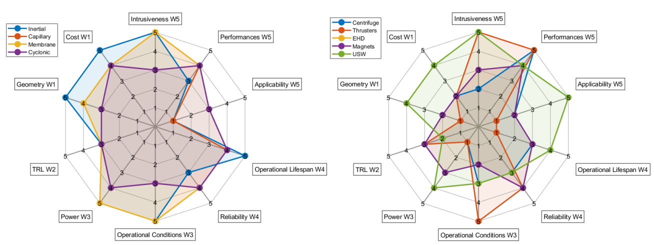
The low score obtained by all the active static approaches except acoustics is mainly due to mass, costs, operational lifespan, intrusiveness, and, above all,

Table 3: Trade-off of analysis of phase separation techniques.

		Techniques								
Criterion	Weighting factor	Passive-static	Passive-static	Passive-static	Active-rotary	Passive-rotary	Active-static	Active-static	Active-static	Active-static
		Inertial	Capillary	Membranes	Centrifugal	Cyclonic	Thrusters	EHD	Magnets	Acoustic
Intrusiveness	5	5	5	5	2	3	5	3	3	5
Performance	5	3	4	4	5	4	5	4	4	4
Applicability	5	1	1	3	2	3	1	2	2	5
Operational lifespan	4	5	4	4	3	4	1	3	3	4
Reliability and maintainability	4	3	4	4	3	4	4	4	4	3
Operational conditions	3	5	5	5	3	3	5	2	2	3
Power consumption	3	5	5	5	1	4	1	3	3	4
TRL	2	3	3	3	3	3	3	3	3	2
Geometry and structure	1	5	4	4	1	3	1	2	2	4
Cost	1	5	4	4	2	4	2	2	2	4
Total score		**123**	**126**	**136**	**90**	**116**	**102**	**98**	**98**	**131**



(a)



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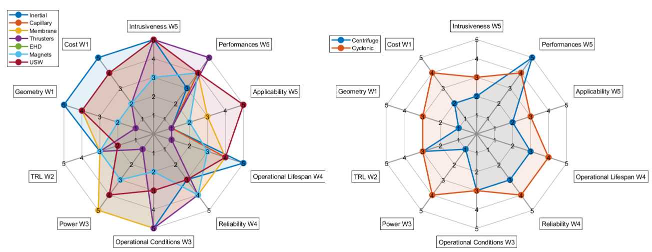

(c)

Figure 15: Comparison of the phase separation techniques: a) All techniques, b) Passive *vs.* active, c) Static *vs.* rotary. "W" followed by a number indicates the weight associated to the requirement in the analysis.

to the applicability to the bioreactor. EHD pumps and magnets require a substantial modification and preparation of the fluids. They demand for dielectric behavior and diamagnetic properties of the liquid, respectively, which reflects on costs and on liquid physical properties (operational conditions, intrusiveness and applicability). Despite having good performance and relative low power consumption, EHD and magnets do not obtain a satisfactory total score. Thrusters represent an approach completely non-intrusive. However, their applicability to bioreactors is very low due to the high cost associated to their continuous use in terms of fuel, which also determines the operational lifespan of the approach. To produce the necessary oxygen in space, the MELiSSA bioreactor will require continuous functioning and, consequently, continuous phase separation.

Among rotary techniques, centrifuges are characterized by significant drawbacks in cost, mass, volume, maintenance, power consumption, intrusiveness on the system (centrifugal acceleration could seriously affect the biological cells risking to kill them), and operational conditions (pressure and temperature). The latter problem also affects significantly the score of passive rotary technologies. Even though cyclonic separators are relatively light, low cost and characterized by low power consumption, parameters mainly related to the pump necessary to generate the pumped loop, the applicability and the intrusiveness can be important drawbacks.

Acoustic approaches get a high total score, thanks to their low weight, non-intrusiveness and promising high performance. The main drawback consists in the influence on the operational conditions, in particular in terms of pressure, since the acoustic techniques are based on the acoustic pressure in order to obtain the desired phase separation, which affects the pressure field in the reactor. In particular, a too high pressure could affect the cell condition, which would significantly worsen the applicability.

Passive static techniques reach a high score in spite of their low applicability. These approaches are low weight, low cost, non-intrusive and have no power consumption. However, if inertial, membranous or capillary approaches were adopted, bioreactors would likely need several geometrical modifications in order to ensure the desired phase separation. Therefore, their applicability might not be compatible with the reactor functioning, which could need a completely different geometry for the inertial or capillary approaches. The difference in score between capillary and inertial techniques is determined by the operational lifespan. The inertial approaches could in principle work as long as desired, while the capillary technology will eventually incur in the clogging of the membranes or porous throats. In addition, inertial separators strictly depend on flow regime and flow conditions. These systems are substantially only auxiliary geometrical structures (wedges, elbows, impingements). Thus, the performance and reliability of inertial separators are considered lower than those of capillary separators and membranes. The difference in score between capillary and membranes is uniquely determined by the higher applicability of the membranes because they have already been tested in other bioreactors. However, their use would affect the illumination inside the LSS considered (*i.e.* light diffusion and intensity in photobioreactors) and would worsen their applicability. Furthermore, passive static techniques are not completely controllable and, therefore, to ensure the desired reliability could be more adequate to use an active solution.

6. Conclusions

The increasing emphasis on long-term human activity in space implies the need of multiphase systems with more flexibility and greater control, low power consumption and lightweight. In this context, a trade-off analysis of phase separation techniques for space applications, in the framework of advanced LSS, has been performed and presented. The results of the analysis have been particularized for the MELiSSA phostosynthesis bioreactor.

The first step of the analysis consisted in the establishment of the requirements and criteria (or trade variables), and a detailed review of the candidate techniques for phase separation. Later, a comparative analysis of the approaches in each criterion has been carried out qualitatively and/or quantitatively, assigning a score to each criterion for each technique.

The trade-off analysis is a tool that gives broad information about the techniques under study, but it is not a perfect representation of them. In addition, there are still some uncertainties associated to some approaches. Therefore, the analysis performed does not define the perfect system. Nevertheless, the analysis allows discarding some of the techniques, focusing on the most promising ones. The result of the performed analysis shows the static passive and acoustic approaches as the most interesting ones for the considered LSS. Neither of them can be discarded at this point. Hence, a natural follow-up of the outcome of this work consists in further experimental (on ground and in microgravity) and numerical work on these techniques for a more accurate evaluation of their feasibility in the MELiSSA photobioreactor.

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