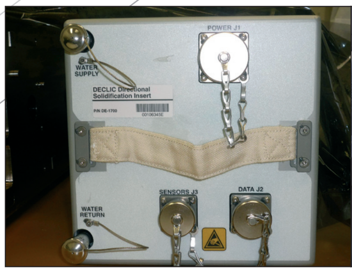
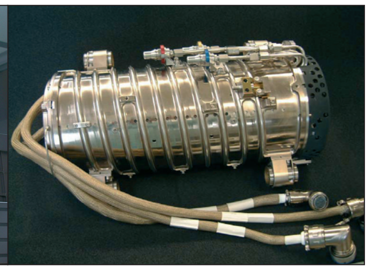
COSPAR 2010

Condensed-matter physics



[Fig. 1]

[Fig. 2]



[Fig. 3]

AUTHOR
B. Zappoli

Microgravity science is the study of physical phenomena masked or modified by gravity on Earth. These phenomena are mainly encountered in fluid phases with strong density gradients (critical fluids) or involving interfaces (solidification processes, foams, emulsions, granular matter). Microgravity can be achieved by balancing the weight by another volume force, like an inertia force in the case of a satellite or a free fall, or like a magnetic force in gravity compensation ground-based devices. Microgravity is also a non reducible property of space flights to which space systems must adapt. Microgravity is thus both a branch of space science that uses space for research and a branch of space technology that uses research for space.

The context

The dominant event in the last two years was the beginning of the full exploitation of the ISS by a six-member crew. Harvest has begun to show the scientific quality of the research but concerns do exist on the return mass capabilities after the space shuttle retirement at the end of 2010. CNES participates via ESA in the research program conducted in the Materials Science Laboratory (MSL) and the Fluid Science Laboratory (FSL) and has developed a facility dedicated to the study of supercritical fluids and the solidification of transparent model materials, DECLIC (DEvice for Critical LIquids and Crystallisation). Involved in this program are 40 laboratories belonging to CNRS and CEA, part of a research agreement between the above-mentioned research institutes and CNES. The budget covering the laboratory needs is in slight increase in 2010 due to new demands to exploit the data from the experiments performed onboard the ISS. The last seminar of scientific prospective held in Biarritz in March 2009 gave mid-term programmatic priorities and gave recommendations on future areas to be explored, including physicochemical aspects of life science and the development of innovative research facilities to prepare for space exploration.

The DECLIC facility

The miniaturized optical and mechanical laboratory DECLIC (Fig. 1) was launched by the space shuttle on August 28, 2009 and installed in the Japanese module Kibo of the ISS, together with two of the three inserts developed so far (High Temperature Insert, HTI, and Directional Solidification Insert, DSI). The third one, ALI (Alice Like Insert), which will continue the research program begun in the MIR station with the ALICE apparatus, was sent to space, in April 2010. The HTI, devoted to the properties of supercritical water, was powered on in December 2009 and will be operated alternately with the DSI until August 2010 from the CADMOS user support centre in Toulouse. After that it will be brought back to the ground to be refurbished (the cell filled with a sodium chloride solution) within the framework of a NASA/CNES cooperation. The study of the migration of salt in a temperature gradient will then be possible. These studies will prepare for the future supercritical water oxidation experiments that are of interest for waste treatment in space and on Earth.

The research onboard the Columbus module

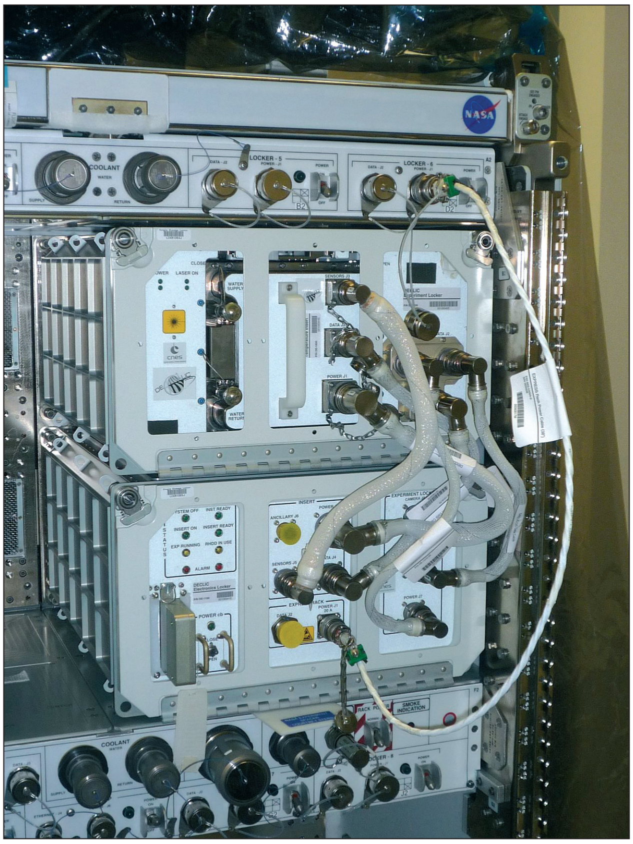
The two facilities devoted to physical sciences onboard Columbus, the MSL and the FSL, host and give resources to inserts devoted to specific experiments. The selection of the experiments is made after proposals by topical teams which gather scientific teams belonging to the ESA Member States. It is within the framework of these topical teams that the French scientists participate in eleven projects. Those using the FSL are: the stability of emulsions (FASES project), the interaction between a drop and a wall (DOLPHIN), the heat transfer during boiling (RUBI), foam ripening (FOAM1), foam stability (FOAM2), dusty plasmas (PKE4), biomimetic object dynamics, and geophysical flow simulation (GeoFlow). Those using the MSL are: the formation of microstructures in 3D samples (MICAST); the transition between equiaxed and columnar growth (CETSOL), the wetting phenomena during crystal growth. 2010 will mainly be devoted to materials science experiments even though the FASES experiment will be performed the same year.

The suborbital and ground-based experiments

The airbus parabolic flight experiment was intensively used to prepare the experiments in the Columbus module and to perform self-standing research. An example of the latter includes the static and dynamic properties of wave turbulence that describe a wide family of physical phenomena, including surface and internal waves in oceanography and meteorology, Alfvén waves in the solar wind, spin waves in solids and quasi-particle transport in semiconductor lasers. The experiments consisted in coating the internal surface of a glass sphere thanks to wetting forces and the absence of gravity drainage. The capillary waves are generated by vibration of the glass sphere. It was possible to observe the wave turbulence over several decades without boundary conditions in the propagation directions. Many other experiments were performed on granular matter dynamics, foams and emulsions. These projects explore the properties of humid foams having a very short life time on Earth due to the gravity drainage. A particular attention is devoted to the capillary drainage, to the ripening (bubble growth by gas transfer) and to the stabilization by addition of particles in connection with the rheologic properties. These foams are interesting models for metallic foams stabilized by metallic oxide nanoparticles. The magnetic field gradient facility in Grenoble was also intensively used to measure boiling heat transfer coefficients in boiling liquid oxygen under variable gravity conditions. An interesting cooperation with space system developers is to be noted as well as a challenging R&T project on the use of high-temperature supraconductors to design large volume, compact magnetic field gradient levitators.

The future

The seminar of scientific prospective of March 2009 recommended to both keep cooperating with space agencies that have access to space and utilize the instruments onboard the European Columbus module of the ISS. The development of the experiments devoted to granular matter dynamics (DYNAGRAN) and to the boiling of a droplet on a substrate have been recommended to be flown onboard the Chinese automated satellite in cooperation with the Chinese Academy of Sciences and the Chinese National Space Agency. Exploitation of the existing inserts of the DECLIC facility, including their upgrading after their return on the ground will be pursued and the development of a new insert dedicated to super-critical water oxidation is strongly encouraged. The SCWM experiments (Super Critical Water Mixture) will use the HTI insert upgraded model to study the migration of salt in a temperature gradient in supercritical water through a cooperation with NASA. Concerning the ground-based facilities, the feasibility study of a large volume levitator for liquid hydrogen will be engaged. Last but not least, the seminar recommended a cooperation between life and physical sciences, in particular in the field of mechanical threshold of gene expression which could lead to new insights on the effect of gravity on living systems. In the same way, an experiment was decided which puts together life and physical laboratories to perform experiments devoted to the understanding of the interaction between artificial circulating phospholipidic vesicles and the walls of a living rat's artery to give information on the endothelial dysfunction and its countermeasures.



[Fig. 4]

Fig. 1: *The DECLIC insert.*
Fig. 2: *Preparation of the DECLIC experiment at the Space Center in Toulouse.*
Fig. 3: *MSL/SQF - Materials Science Laboratory Solidification and Quenching Furnace.*
Fig. 4: *DECLIC placed in an express rack onboard the ISS.*

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Condensed-matter physics

Hydrodynamics study of oxygen under variable magnetic acceleration.

Etude de l'hydrodynamique de l'oxygène sous accélération magnétique variable.

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Abstract

Partial or total compensation of Earth gravity has already been achieved in pure materials submitted to a magnetic field gradient. A new step is accomplished by reproducing on Earth the fast change of acceleration of spacecrafts. This permits the detailed study of the transient behavior of fuel in rocket tanks. By acting on the current delivered to the two superconductive coils of the OLGA facility, it is possible to rapidly change the acceleration level in the oxygen contained in the experimental cell.

L'utilisation d'un champ magnétique à gradient permet une compensation partielle ou totale de la gravité terrestre dans des matériaux purs. Les changements rapides d'accélération dans des fusées peuvent être reproduits pour étudier le comportement transitoire des ergols contenus dans les réservoirs de fusée. En agissant sur le courant délivré aux deux solénoïdes d'Olga, il est possible de changer rapidement le niveau de gravité dans l'oxygène contenu dans la cellule expérimentale.

Partial or total compensation of Earth gravity (g) can be achieved for solid, gas and liquid phases of pure materials when submitted to a steady magnetic field gradient. This has been the object of the OLGA (Oxygen Low Gravity Apparatus) facility at CEA-Grenoble [1] which works with pure oxygen. Another important issue in the management of fluids in space is concerned with the transient behavior of rocket fuel when the acceleration is rapidly changing, *e.g.* during the rocket engine shut-down or reignition. To study the transient hydrodynamics in these fluids, the electric and cryogenic parts of the magnetic levitation facility OLGA were modified and a new experimental cell was designed.

As shown on Fig. 1, the superconductive coil of OLGA is made up of two concentric solenoids that are powered by two power supplies. The rapid gravity variation is performed by discharging quickly (the time constant is 340 ms) the current from the internal solenoid. The gravity level in O_2 contained in the experimental cell can be changed either from overcompensation of gravity (-0.5 *g*) to zero gravity (0 *g*) or from zero gravity (0 *g*) to reduced gravity (0.4 *g*) thus simulating the deceleration or acceleration of the fuel tank.

Due to the electromagnetic coupling, the external coil current tends to vary and a voltage appears at its edges. A specific electrical supply was thus designed to deliver an opposite voltage to the external coil at the same time so as to keep its current stable during the transition.

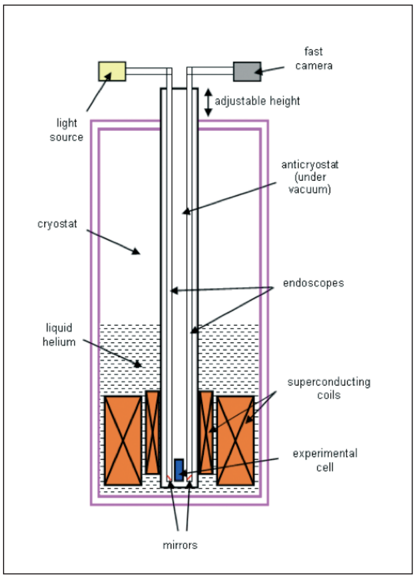
The experiments are performed in a cylindrical cell (Fig. 2). The sapphire cylinder (30 mm diameter and 100 mm length) is closed by two copper flanges, the temperature of which is regulated within ±0.01 K. The oxygen, taken from a gas bottle, is condensed into the cell at 90 K. When the cell is filled to about 80%, the current corresponding to the required compensation of gravity is applied to both solenoids and the liquid-vapor interface is slowly transformed into a nearly spherical bubble (see picture t_0 + 1.4 s in Fig. 3). The bubble size can be adjusted with the pressure in the cell. The cell is isothermal. Oxygen is kept at a temperature of 90 K during the experiments.

Both cases were studied with the two-phase O_2 (liquid + saturated vapor) at 90.1 K [2]. Movement of the interface could be observed with a 500 frame-per-second camera during the transition (Fig. 3-4). During the transition from -0.5 *g* to 0 *g* (Fig. 3) the liquid-vapor interface is initially flat and the vapor phase is located below the liquid phase (negative gravity). Then, the vapor phase gradually gets a typical round shape as expected under microgravity. Instabilities are visible on the interface at t_0 + 0.4 s and t_0 + 0.6 s. In the transition from 0 *g* to 0.4 *g* (Fig. 4), the vapor bubble is initially round in weightlessness conditions. As soon as the gravity increases, the bubble begins to move upwards because of the buoyancy force and a liquid jet appears inside the bubble. The jet is visible after t_0 + 0.125 s. The bubble shape is deformed by a Kelvin-Helmholtz instability.

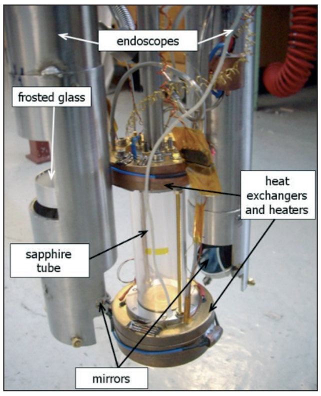
The new configuration of the magnetic levitation facility OLGA at CEA-Grenoble enables fast variations of acceleration (340 ms time constant) to be performed. The maximum amplitudes available are from -0.5 *g* to 0 *g* and 0 *g* to 0.4 *g*. In particular, the configurations that correspond in spacecraft engines to a shut-down or a reignition can indeed be reproduced on Earth.

This work was supported by CNES and the Air-Liquide company.

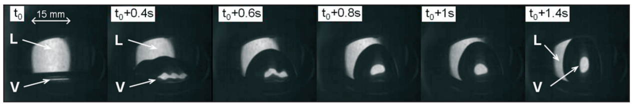
The authors gratefully thank J. Chartier, P. Bonnay, S. Bressieux, and J.-M. Mathonnet for their contributions.



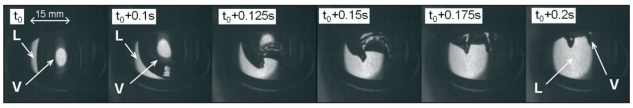
[Fig. 1]



[Fig. 2]



[Fig. 3]



[Fig. 4]

***Fig. 1**: Schematic view of OLGA.*
***Fig. 2**: A photography of the experimental cell with its endoscopes.*
***Fig. 3**: Interface behavior during a -0.5 g→0 g transition that corresponds to a rocket stop; t_0 is the starting time of the transition; L indicates the liquid phase and V the vapor phase. The interface is at rest in both the first and the last picture.*
***Fig. 4**: Time evolution of the interface shape during a 0 g→0.4 g transition that corresponds to the rocket acceleration; t_0 is the starting time of the transition; L indicates the liquid phase and V the vapor phase. The interface is at rest in the first picture.*

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COSPAR 2010

Condensed-matter physics

Cryogenic propellant in orbit: experimental data to validate numerical tools.

Ergols cryogéniques en orbite : les données expérimentales pour valider les codes numériques.

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Abstract

To prepare developments of future cryogenic upper stages of space launchers able to perform coasting phases, a good comprehension and a precise modelisation (through CFD tools) of propellant behavior are necessary. During these ballistic phases, cryogenic propellant will no longer settle at the tank bottom under the influence of gravity, instead, cryogenic liquids will spread along tank walls (Fig. 1) and are bound to vaporize at the contact of the hot walls.

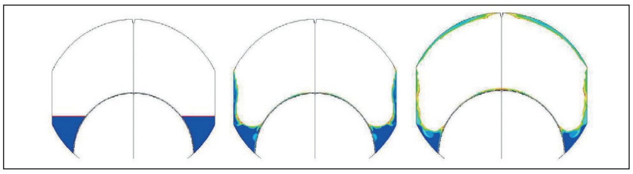
Afin de préparer les développements des futurs étages supérieurs cryogéniques de lanceurs capables de réaliser des phases balistiques, une bonne compréhension et une modélisation précise (par des codes CFD) du comportement des ergols est indispensable. Pendant ces phases balistiques, les ergols cryogéniques ne seront plus tassés au fond du réservoir sous l'effet de la gravité, ils vont se répandre le long des parois (Fig. 1) et risquent de se vaporiser au contact des parois chaudes du réservoir.

This Computational Fluid Dynamics (CFD) tool will be able to model cryogenic propellant behaviors during all phases of a space launch: from the tank pressurization on the launch pad up to the end of the draining of the upper stage tank, including future ballistic phases.

Important work has been performed in the past decade with major model development and validation work thanks to on-ground cryogenic experiments and to in-flight tests with similitude liquids. However, two main types of data are missing:

1. Data concerning heat and mass transfer on walls for cryogenic propellant (liquid oxygen and liquid hydrogen) in low gravity.
2. Global behavior of cryogenic liquid in tanks (temperature and pressure evolution coupled to free surface behavior).

Up to now, some benchmarks have enabled to better understand specific aspects of liquid behavior in tanks and validate some models of numerical codes, mainly for non zero-gravity conditions. For zero gravity, or low gravity conditions, tests performed at this time in Europe are not fully representative of cryogenic fluids. Realization of in-flight tests with representative conditions is a difficult and costly task. In the past, lots of boiling experiments were performed, but data were obtained with similitude liquid and with unsteady conditions. Use of similitude fluid is a good approach to understand the physics



[Fig. 1]

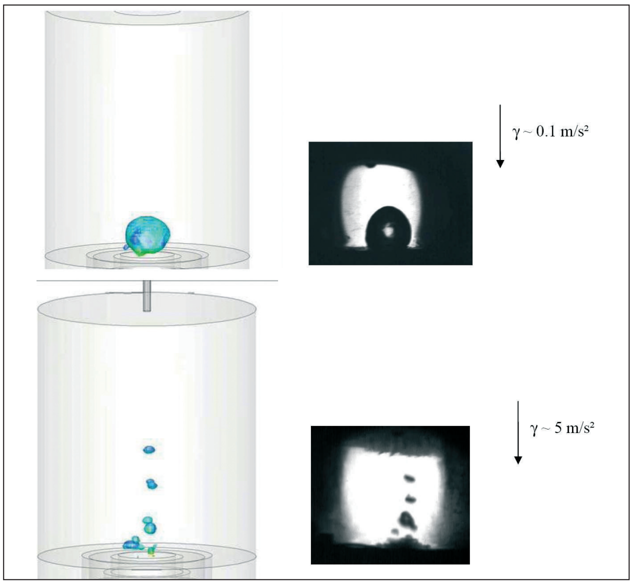
[Fig. 3]

phenomena of heat and mass transfer on walls. However, our lack of knowledge concerning the boiling phenomenon and low gravity effects lead us to avoid empirical determination of heat and mass transfer for liquid oxygen or liquid hydrogen.
The use of the Oxygen Low Gravity Apparatus (OLGA, developed by CEA/SBT with Air Liquide and CNES funding) is a good example of the association of applied science (boiling data of liquid oxygen in low gravity to be used directly) and fundamental science (possibility to get influence of gravity residual levels) to understand boiling mechanisms.

Even if the size of the test cell is limited (3 cm diameter in order to be within 0.05 *g* of residual gravity at the extreme corner of the test cell), this apparatus has some advantages for our application:

1. To be able to wait for established phenomenon (no constraints to get thermally stabilized points).
2. To use different gravity values in order to have the real influence of this parameter –OLGA is able to get a residual gravity of 0 *g*, 0.1 *g* or 0.5 *g* (or Lunar or Martian equivalent gravities).
3. To know precisely the residual gravity field and to be able to impose it in CFD models.

Thanks to this apparatus and the test cell realized, boiling data were obtained for liquid oxygen for different gravity values and other parameters variations representative of tank conditions (pressure, sub-cooling level, *etc*.). These data and associated boiling behavior were also compared to numerical code. The first iterations performed in 2008 and 2009 including boiling tests and boiling computation are very promising with very close dynamic behavior of vapor created (Fig. 2): bubble size, departure frequency, *etc*. Thanks to the data obtained by experimental boiling tests, CFD can now predict precisely the behavior of vapor bubbles created for a defined temperature difference.
For the other subject concerning global data in tanks, a risk mitigation approach was set up. Before realization of costly and long-term experimental benches with cryogenic fluids on sub-orbital or orbital supports, tests in 0 *g* parabolic flight were performed in 2009 with the test bench named “Cry0genic”. First results were obtained in March 2009 during the CNES 75th parabolic flight campaign.



[Fig. 2]

This test bench was the first instrumented test cell with liquid nitrogen to be flown in a parabolic aircraft. A lot of specific instrumentation was included in the test cell in order to appreciate global thermo-hydraulic behavior of liquid nitrogen in low gravity: non-intrusive level sensors (to appreciate surface wetted by liquid), temperature sensors, pressure sensors, digital video camera, *etc*.

During each parabola performed by the aircraft, the residual gravity fell around 0 with some dynamic perturbations. By the location of “Cry0genic” in the aircraft, the residual gravity was in the opposite direction during some periods of time of up to 15 s. During these periods, the liquid was pushed towards the top of the test cell and boiling occurred at this top wall, with bubbles going downward (Fig. 3).
This test bench had a double objective:

1. To prepare future in-flight experiment with larger test cell and better microgravity conditions.
2. To get the first global data in low *g* with cryogenic liquid to validate numerical models.

Concerning the first objective, this experiment confirms and supports our flight predictions and technologies potentially useful for future in-flight experiments (non-intrusive level sensors for example).
The second objective was also successfully reached with plenty of data obtained in real flight with liquid nitrogen. Many computations are now running to validate the numerical method used.

Thanks to these tests in parabolic flight with liquid nitrogen, future in-flight experiments through sub-orbital or orbital platform will be set-up with more confidence.
The presented work was supported by CNES/DLA co-funding.

Fig. 1*: Schematization of the potential behavior of liquid hydrogen wetting tank walls during the ballistic phase (colored by liquid temperature).*
Fig. 2*: Comparison of CFD result (left) and experimental result (right) for dynamic behavior of oxygen bubbles created by boiling close to 0 g condition (top) and 0.5 g condition (bottom).*
Fig. 3*: Comparison of CFD free surface and vapor bubbles of nitrogen during the parabola.*

Condensed-matter physics

Towards a bottom-up approach of blood flow and application to microgravity.

Vers une approche bottom-up *de l'écoulement sanguin et application à la microgravité.*

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Abstract

Red Blood Cells (RBCs) interact in a non-trivial manner with each other and with the blood vessel walls, two ingredients governing blood rheology. Flow resistance and blood diseases critically depend on the endothelial layer of blood vessels. Microgravity affects the stimulation of the endothelium, potentially leading to cardiovascular dysfunctions. Intricate dynamics of RBCs is described together with some endothelium effects in hemodynamics.

L'interaction entre globules rouges et celle avec les parois endothéliales des vaisseaux sanguins sont des ingrédients majeurs pour la rhéologie du sang. La résistance à l'écoulement ainsi que des pathologies sanguines dépendent foncièrement de l'endothélium. La microgravité affecte sa stimulation pouvant conduire à des dysfonctionnements cardiovasculaires. Cet article décrit la dynamique complexe des globules rouges et certains effets de l'endothélium en hémodynamique.

After nearly a century of research on blood, the understanding of the basic blood flow mechanisms at the cellular level (at the scale of RBCs, platelets, *etc.*) is still an open issue. Blood is a complex fluid and the description of its flow properties does not follow the traditional Navier-Stokes law known for simple fluids (*e.g.* water). Until now blood flow has been described by means of phenomenological continuum models that require many assumptions which are difficult both to justify and validate [1]. The macroscopic law of blood flow should carry information on the microscopic scale, such as the orientation of the cells, their individual and collective dynamics, their hematocrit, *etc*.

RBCs consist of a bi-layer of phospholipidic membrane (Fig. 1) containing several proteins (*e.g.* ion channels), endowed underneath with a cytoskeleton (a cross-linked network of proteins, also called the spectrin network) which confers a shear elasticity on RBCs. The interior of the RBC is a solution of hemoglobin which is for a healthy cell a Newtonian fluid.

A closed pure phospholipidic (*i.e.* no proteins) bi-layer membrane is called vesicle, or liposome (Fig. 1). It constitutes a simple model for studying mechanical and viscoelastic properties of real cells, such as RBCs.

The interior of a blood vessel is made of an endothelial layer which is protected on top by a brush-like bio-polymer called glycocalyx about 1 µm thick, which makes blood flow resistance about twice higher in blood vessels than in glass tubes of the same diameter. A notable fact in blood circulation is that blood viscosity exhibits quite an astonishing effect: the viscosity may dramatically decrease for a given hematocrit by reducing the blood vessel diameter (Fahraeus-Lindqvist effect) [1].

Under microgravity, the endothelium is less stimulated (vascular hypo-responsiveness). The absence of stimulation is known to cause a degradation of the endothelium that should have an impact on blood flow properties, a possible cause for cardiovascular diseases.

Research based on a bottom-up approach of blood flow has just begun theoretically and experimentally, for a recent review see [2]. The first prominent effect exhibited by RBCs or vesicles in a shear flow close to a substrate is their ability to experience a lift force. Under gravity the weight of cells acts against the lift force and is capable of stopping the lift at a distance close to the wall. In microgravity, parabolic flights and sounding rockets, the lifted vesicle could travel long distances away from the wall. Thus, data within large interval variation of the distance from the wall could be collected, allowing to ascertain the physical laws. It has emerged from these studies [2] that the lift force obeys the following scaling law $F\sim\eta\gamma R^3/h$, where R is the vesicle size, η is the suspending fluid viscosity, γ is the shear rate and h is the distance of the vesicle from the wall. This lift is quite selective with the cube of the size. This implies that large cells will be centred, while small ones should remain off-centred, *i.e.* pushed towards vessel walls.

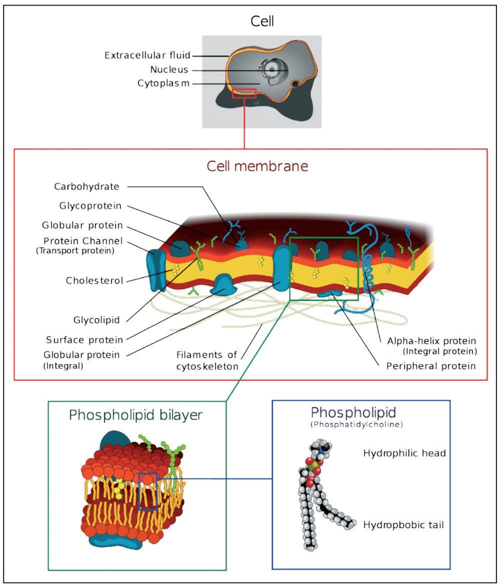
Another origin of the lift force is due to a curvature of the flow, like in a Poiseuille flow. Both experiments and numerical simulation showed that the scaling of the lift force with the distance from the wall is drastically different from the previously discussed one (which behaves as 1/h), namely $F\sim1/h^2$. The lift force acting on the RBCs is believed to induce a depletion layer near the vessel wall, which leads to the Fahraeus-Lindqvist effect. Note also that under shear flow RBCs and vesicles exhibit quite rich dynamics that impact on rheology [2].

A longstanding dilemma of RBCs, recently solved, is why they adopt a non symmetrical shape called "slipper" shape (Fig. 2 bottom) in small blood vessels. A key result [3] is that the parachute symmetric shape (Fig. 2 top) is unstable, while the slipper shape is stable. In addition, the slipper shape motion favors mixing of hemoglobin solution inside the cell and thus, it enhances oxygen supply in tissues.

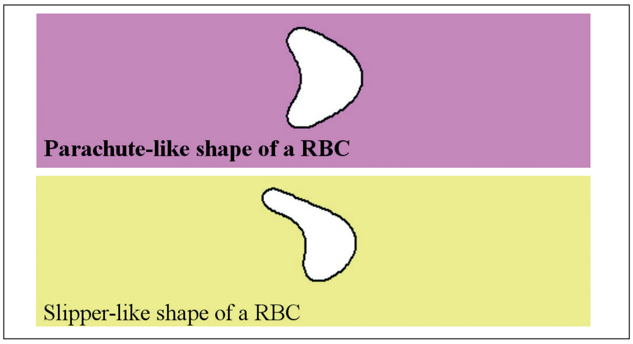
The endothelium plays a crucial role in the regulation of microvascular homeostasis and local blood flow. Under normal conditions, the endothelium induces vasodilatation, limits vascular inflammation and decreases platelets adhesion. Blood flow exerts shear stress forces at the surface of endothelial cells. A chronic decrease in shear stress in vascular lumen impairs endothelial functions. Endothelium is impaired at the microcirculatory level after simulated weightlessness by bed-rest and preserved by countermeasures with physical exercise [4]. Surprisingly, at the macrocirculatory level, endothelial vasodilatory functions appear preserved or enhanced [5]. Shear stress forces are different in large and resistive arteries. Bed-rest conditions seem to increase shear stress at the macrocirculatory level but to decrease shear stress at the microcirculatory level because of physical inactivity.

Endothelial dysfunction at the microcirculatory level might contribute to bed-rest induced pathologies such as muscle atrophy and changes in energy metabolism. Endothelial dysfunction might participate in the decrease of VO_2 max, one of the symptoms of cardiovascular deconditioning. However, relationship between endothelial dysfunction and orthostatic tolerance needs to be clarified.

To better understand the mechanisms of endothelial dysfunction under microgravity conditions, it appears necessary to study the interactions between physical forces and the endothelium.



[Fig. 1]



[Fig. 2]

***Fig. 1**: A schematic view of a RBC membrane.*
***Fig. 2**: Top: parachute symmetric shape. Bottom: slipper non-symmetric shape. These are results of numerical simulations [3].*

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