Ground-based activities in preparation of SELENE ISS Experiment on Self-Rewetting Fluids

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Abstract. SELENE (SELF rewetting fluids for thermal ENergy management) is a microgravity experiment proposed to the European Space Agency (ESA) in response to the Announcement of Opportunities for Physical Sciences. Main objectives of the microgravity research onboard ISS include the quantitative investigation of heat transfer performances of “self-rewetting fluids” and “nano self-rewetting fluids” in model heat pipes and validation of adequate theoretical and numerical modelling able to predict their behaviour in microgravity conditions. This article summarizes the results of ground-based research activities in preparation of the microgravity experiments. They include: 1) thermophysical properties measurements; 2) study of thermo-soluto-capillary effects in micro-channels; 3) numerical modelling; 4) thermal and concentration distribution measurements with optical (e.g. interferometric) and intrusive techniques; 5) surface tension-driven effects and thermal performances test on different capillary structures and heat pipes; 6) breadboards development and support to definition of scientific requirements.

1. Introduction

Two-phase flow devices based on evaporation and condensation, surface tension and capillary effects, are very frequently used as thermal energy management systems in many applications including electronics cooling, air conditioning, propulsion, power generation, energy recovering, chemical engineering. Research and development activities are generally concerned with development of advanced heat pipes, vapour chambers or thermal ground planes for efficient cooling of semiconductor and integrated circuit devices, since energy dissipation becomes critical to their operation. In the space applications, increase in size of space platforms and future exploration missions will require a large...
amount of heat to be dissipated by large space radiators. Efficient thermal control in space and the reduction of moving mechanical elements by two-phase closed-loop systems, becomes of crucial importance.

The two most important objectives in electronics or other cooling engineering applications, namely the reduction of the device maximum temperature and the minimization of temperature gradients on the device surface, can be efficiently achieved by the use of micro-grooved heat pipes and/or selecting suitable working fluids.

The research activities presented in this paper deal various processes governing heat transport capacity of the two-phase flow devices and in particular on the heat transfer performances of binary or multi-component heat transfer fluids with particular surface tension, called “self-rewetting fluids”, i.e. liquids with a surface tension increasing with temperature and concentration. As pointed out in [1-9], thermophysical properties, like surface tension, wettability and thermal conductivity, at different temperatures, are of crucial importance not only for binary mixtures, but also for a number of ternary aqueous solutions with relatively low freezing point and for nanoparticles suspensions. Some of them interestingly exhibit the same anomalous positive surface tension gradient with temperature as binary self-rewetting solutions. Since in the course of liquid/vapour phase change, self-rewetting fluids behaviour induces a rather strong liquid inflow (caused by both temperature and concentration gradients) from the cold region (where liquid condensates) to the hot evaporator region, several interesting space and terrestrial applications may be envisaged [10].

In this general framework, a cooperative international project supported by ESA and JAXA is under development to contribute to the understanding of the basic fluid dynamic and physico-chemical mechanisms occurring in these multi-component two-phase systems and particularly on the interplay between heat transport and surface and bulk thermophysical properties. To pursue the above objective, the behaviour of non-isothermal self-rewetting liquids will be experimentally investigated onboard the International Space Station under microgravity conditions.

This article is organized as follows. The general scientific and technological motivations and concepts of the microgravity experiment SELENE are summarized in section 2, including main objectives, preliminary design concepts and requirements and description of the experimental procedure. Fundamental theoretical, experimental and numerical results of ground activities on the subject are summarized in the next paragraphs. In particular, laboratory results achieved on ground are presented, including thermophysical properties measurements, flow visualization experiments with transparent cells, optical and interferometric analyses. Final comments will conclude the article.

2. SELENE Experiment on ISS

SELENE (SELf rewetting fluids for thermal ENergy management) is a microgravity experiment proposed to the European Space Agency (ESA) in response to the Announcement of Opportunities (AO 2009) for Physical Sciences. The proposal received a favourable scientific and technical review and selected for inclusion in the ELIPS research pool, approved by the ESA Programme Board for Human Spaceflight, Microgravity and Exploration. The project is carried out under a cooperative ESA-JAXA programme.

The main objectives include the quantitative investigation of heat transfer performances of self-rewetting fluids in model heat pipes and validation of adequate theoretical and numerical modelling able to predict their behaviour in microgravity conditions. Once the models have been validated, they can be extended and applied also to terrestrial applications.

Microgravity offers the opportunity to avoid gravity effects and to analyse in detail typical flow patterns occurring only in the space environment, in relatively large systems, offering the opportunity to perform systematic experimental investigations of the processes, considering a large number of experimental conditions typical of space and terrestrial heat pipes. For this reason the experiments will use transparent test cells, to allow direct flow visualization, coupled with optical and intrusive diagnostic techniques to measure thermal/compositional fields.
Main physical mechanisms that shall be investigated include:

- surface tension-driven and Marangoni flows induced by evaporation, condensation, temperature and concentration gradients
- two-phase flow and liquid-vapour distribution
- influence of the vapour temperature and pressure on the flow regime
- effect of the length of the evaporator/condenser regions
- influence of the liquid fraction
- effect of the nanoparticles type and concentration on the heat transfer performances
- effect of the heat pipe cell surface geometry (e.g. single capillary channel vs. structured surface)
- liquid film stability and the dry patch formation in each heat pipe configuration.

The SELENE experiment shall feature a heat pipe cell (ideally a pair of cells) mounted on a thermal conditioning platform (see figure 1). The heat pipe cell (pair) shall be interchangeable to allow the study of numerous cells using the same facility.

The implementation of pairs of heat pipe cells could allow the parallel study of two liquids simultaneously or sequentially, but in the same configuration and settings.

Each cell represents a half-heat pipe model with one groove of appropriate cross section shape and size machined into the bottom surface. The heat pipe cells are prepared on-ground and filled with the experiment liquid. The cells may also include certain (mostly intrusive) measurement devices, such as thermal sensors. The top window of the heat pipe cell is transparent, which enables the use of various optical diagnostics (infrared observation, interferometry). Furthermore, optionally velocimetry measurements shall be possible as well. In each heat pipe cell temperature and concentration sensors shall provide local measurements of the liquid properties.

For each heat pipe, evaporation is promoted at the hot side (evaporator) with a controllable heat input while the temperature at the other end (condenser) should be controlled and kept at a lower value. For a given temperature difference, corresponding to a prescribed thermal power, the evaporated liquid will condense at the cold side where heat will be removed and the liquid condensate will be driven back to the evaporator flowing along the channel by the capillary effect and/or by the inverse Marangoni effect. The heat input (evaporator) and the temperature (condenser) can then be fine-tuned.
with dedicated elements. The investigation of the evaporation and condensation-driven behaviour of the liquid in this cell, when subjected to different heat stimuli is the main objective of the experimental research.

Main experiment scientific required measurements include:

- heat power provided at the evaporator section
- heat exchanged at the condenser section
- temperature distributions along the liquid-vapour interface and in the liquid at different positions along the cell, from the evaporator to the condenser
- concentrations in the liquid at different positions along the cell, from the evaporator to the condenser
- liquid distribution and in particular film thickness and shape of the liquid-vapour interface from the evaporator to the condenser using visual observation and quantitative analysis (e.g. interferometric techniques) during heat pipe operations, i.e. from relatively low power up to the dry-out limit for the different investigated working fluids
- flow visualization shall be considered also for liquid velocity measurements

A layout of a possible experimental heat pipe cell is shown in figure 2. It shall include in the “bottom surface” part a metallic surface (copper or aluminium) with a dedicated hydro- and oleophilic channel (groove) connecting the evaporator to the condenser in the nominal configuration. Nevertheless, different surface structures shall be possible as well.

The shape and size of the channel shall be designed according to the maximum thermal power and heat flux density to be representative of ordinary heat pipes.

As a baseline, the bottom surface of the groove shall be prepared with very small roughness (like an optical mirror) or eventually coated (e.g. with silver or gold) in such a way that the optical quality allows interferometric measurements in reflection mode. Nevertheless, certain samples with different surface roughness and/or structuring will be also foreseen (without interferometric measurements).

The opposite surface of the cell (“top window” in figure 2) shall be made of an optically transparent material with relatively high thermal conductivity (e.g. sapphire).

![Figure 2. Possible Heat Pipe Cell layout. A single rectangular groove is shown but different surface structures shall be considered.](image)

The experiments require very long duration, therefore scientific and technological results can be obtained only on ISS using a dedicated test container.

For measurements of temperature and concentration distributions a set of temperature and concentration sensors shall be mounted on each pipe. In particular micro-sensors for measurements of
liquid refractive index will be considered, in order to evaluate the liquid concentration once the temperature is known.

CCD, Infrared Camera and Interferometric analysis will complete the investigation of the basic fluid physics mechanisms occurring in the heat pipe model, to detect the liquid fraction distribution within the cell, the liquid-vapour interface shape, the thermosolutal and liquid velocity distributions.

3. **Ground-based research activities**

In what follows, a number of ground research activities, in preparation of the microgravity research, will be summarized.

3.1. **Characterization of thermophysical properties of self-rewetting fluids and nanofluids**

As discussed in [11], main thermophysical properties of interest for utilization of self-rewetting fluids in thermal energy management devices include surface tension, contact angle, latent heat of vaporization, thermal conductivity, freezing point. These properties have been investigated for a number of binary and multi-component self-rewetting solutions including water-alcohol solutions (based on Butanol, Pentanol, Exanol, Heptanol, etc.) as well as in low freezing point mixtures (brines) with relatively low concentrations of the same alcohols [11]. Comparison between different working fluids show that generally self-rewetting fluids exhibit better performances in terms of surface tension and wetting behaviour, in comparison to the base liquids. Furthermore, preliminary tests on heat pipes in different configurations pointed out better thermal performances when self-rewetting fluids or self-rewetting brines are used to replace common heat transfer fluids like water.

Particular attention has been dedicated to the study of the thermophysical properties of nanofluids based on water/alcohol solutions. They include self-rewetting nanofluids based on silver or gold nanoparticles or nanofibers [9], or nanofluids with suspended carbon nanostructures, in particular single-wall carbon nanohorns [12]. In [9] the authors have shown that “self-rewetting nanofluids” containing aqueous-butanolic solution with microwave-assisted synthesized silver nanoparticles exhibit dryout limits in heat pipes almost twice as high as that of base working fluid heat pipe and this could be explained by the enhancement of the surface tension gradients with temperature, due to the dependencies changes of silver nano-self-rewetting fluids. Since these self-rewetting nanofluids contained very dilute silver nanoparticles, other thermophysical properties such as thermal conductivity and viscosity were almost same as those of base fluid.

Another research line was dedicated to self-rewetting nanofluids prepared suspending, in butanol-water solutions, single wall carbon nanohorns (SWNH), produced by arc discharge [12]. In this case, surface tensions measurements reveal the self-rewetting behaviour of the nanofluids as the self-rewetting base solutions have shown that the presence of the carbon nanoparticles does not affect the surface tension and contact angles properties of these fluids, in comparison to the corresponding base fluid, i.e. a binary butanol aqueous solution. On the other hand, thermal conductivity measurements performed with the parallel plate technique pointed out a significant enhancement of the equivalent thermal conductivity due to the presence of the carbon nanohorns.

Preliminary heat transfer analysis of heat pipes filled with self-rewetting nanofluids based on carbon nano-horns confirm improved performances in comparison to other self-rewetting fluids.

3.2 **Flow visualization and interferometric analysis**

Research activities have been focused on numerical simulations and laboratory experiments in transparent cells for the visualization and analysis with optical diagnostic systems of fluid flows in presence of thermal gradients.
Some basic fluid-dynamic mechanisms related to the behaviour of wickless transparent heat pipes with self-rewetting fluids have been investigated in [6]. In particular, the interesting behaviour of “inverse” thermocapillary bubble migration was pointed out (see figure 3) in transparent capillary tubes, showing the different Marangoni effect in self-rewetting fluids compared to ordinary liquids. This phenomenon has been discussed to show the potential advantages of the new working fluids and confirmed by the thermal characterization of wickless heat pipes filled with water and with self-rewetting fluids.

Experiments with binary solutions of water and long-chain alcohols have confirmed the different boiling behaviour in heat pipes filled with self-rewetting fluids in comparison to pure water [6]. For the self-rewetting fluid the evaporation region contains more liquid in comparison to water, which also implies spontaneous liquid supply to higher temperature region and vapour slug behaviour near the heating region implies a rather strong shear stress between vapour and liquid film.

In [13] thin optically transparent cuvettes with lateral heating allowed the development of a nearly 2D flow, good thermal boundary conditions and minimization of the liquid meniscus; in addition this configuration is similar to typical devices for heat transfer applications. The target of the experiments was to observe the Marangoni flow driven by the thermal and solutal gradients along the liquid-vapor interface. The investigated fluids include two ordinary liquids (water and ethanol) and water/alcohols mixtures (self-rewetting fluids), in particular water-butanol 5%wt, water-heptanol 0.2%wt.

As discussed in [13], for self-rewetting solutions, due to the evaporation–condensation phenomena, both thermo-capillary and solutal Marangoni effects are present. Indeed, any imposed temperature difference along a liquid-vapour interface creates a surface concentration gradient, alcohol evaporates in the hot region of the surface and condensation occurs at the cold side. For this purpose, flow visualization experiments have been accomplished using optical diagnostic systems, in particular, a parallel background illumination system to visualize tracer particles and a two wavelength Mach-Zehnder interferometer. The latter technique allows one to evaluate, once the temperature and concentration dependence of the refraction index is known at each wavelength, the temperature and concentration profiles. In this way the different contributions related to thermo-capillary and solutocapillary effects can be independently evaluated. In particular, based on the measured surface tension derivatives for the different binary solutions investigated, the different driving actions have been predicted from the temperature and concentration distributions, for a positive mixture (like water-ethanol) and a self-rewetting water-butanol solution.

The measured temperature and concentration maps shown in figures 4 and 5 point out that, as
expected, in pure liquids ordinary Marangoni flow is directed towards the cold side, but self-rewetting solutions exhibit a self-rewetting behaviour, i.e. liquid at the interface directed towards the hot side. In particular, the surface velocity, directed from the cold (left) towards the warm (right) side is responsible for an evident “inverse” deformation of the isotherms at the liquid-vapor interface. The numerical results are in agreement with the experimental results. Further details can be found in [13].

![Figure 4. Marangoni convection in Ethanol. Interference fringes and temperature distributions, experimental and numerical [13]. The liquid layer is 1mm depth. The cell length is 4cm. Only the central part is shown. The temperatures at the hot and cold side are 60°C and 40°C](image)

![Figure 5. Marangoni convection in water-heptanol solution. Interference fringes and temperature distributions, experimental and numerical [13]. The liquid layer is 1mm depth. The cell length is 4cm. Only the central part is shown. The temperatures at the hot and cold side are 70°C and 40°C](image)

### 3.3 Theoretical and numerical activities

Preliminary theoretical and numerical simulations are in progress at the University of Naples to identify the geometry and experimental conditions for the ISS experiment. In particular, the main objective is the development of analytical or numerical models able to predict the dry-out (capillary) limit of microchannels in microgravity, in order to identify the expected experimental conditions. A model for fluid flow and heat transfer in the micro-channel of arbitrary V-shaped cross section has been developed due to evaporation and condensation. The liquid meniscus radius changes with position in a micro-channel, and the liquid pressure is given by the Young-Laplace equation. The model allows one to evaluate the dry-out limit of micro-channels with different cross section.

The model equations [14] are based on the following assumptions: (i) one dimensional steady incompressible flow along the length of heat pipe; (ii) uniform distribution of heat input; (iii) negligible heat dissipation due to viscosity; (iv) constant pressure in the vapor region in the operating range of temperature; (v) one dimensional temperature variation along the length of heat pipe; (vi) negligible shear stress at the liquid-vapor interface (zero Marangoni effect); complete wetting of the liquid (zero contact angle).

The heat pipe has three sections – the evaporator takes up dissipated heat, the condenser releases the heat to the surroundings, and the adiabatic section transports the heat from the evaporator to the condenser. Due to evaporation and condensation, the liquid meniscus radius changes with position in a micro-channel, and the liquid pressure is given by the Young-Laplace.

The pressure difference generates the capillary pumping for the liquid flow from the condenser to the evaporator. In particular, the liquid is pushed from the cold end to the hot end due to decrease in the radius of curvature caused by the intrinsic meniscus receding into the corner. The liquid film gradually becomes thinner and more curved (lower radius of curvature) as the liquid recedes further towards the apex of the corner (see figure 6).
The analytical model provides the equation for the dimensionless curvature radius as function of the local coordinate and of the input power at the evaporator, if the fluid properties (viscosity, surface tension, latent heat, etc.) are known. Furthermore, the critical heat input ($Q_{cr}$) i.e. the maximum heat transport capacity of a micro-grooved heat pipe, without generating any hot spot in the heat pipe, can be evaluated.

In particular, according to order of magnitude scaling analysis, the maximum dimensionless heat flux at the evaporator/condenser (scaled with reference thermophysical fluid properties) is proportional to the square of the groove depth ($a$) to length ($L$) ratio:

$$\frac{Q}{(L_a)(\rho H, \sigma/\mu)} \propto \left(\frac{a}{L}\right)^2$$

where $Q$ is the heat input and $Q/(La)$ is the heat flux density (W/m$^2$), $\rho$, $H_V$, $\sigma$ and $\mu$ are the density, the latent heat of vaporization, the surface tension and the viscosity respectively.

Figure 7 shows the predicted evolution of the dimensionless film thickness along a microchannel with length 15 cm, cross section of width 6mm, half angle 45°, in presence of different input powers, until dry-out. It is interesting to see also the corresponding power densities in figure 8.
A three-dimensional numerical model has been developed to better investigate the influence of some parameters like filling ratio (i.e. ratio between the volume of the liquid and the volume of the fluid cell), and the wetting properties of the liquid on the dry-out limit. Figure 9 shows the geometry (in particular the rectangular groove) of the investigated configuration and the corresponding three-dimensional grid. The cross section of the bottom groove is 4mm x 4 mm. The total length is 15 cm.

The numerical model, based on the commercial FLUENT solver with ad-hoc user defined functions, is able to solve the energy and fluid dynamics equations for a two-phase system (liquid and vapour) in presence of evaporation and condensation.
Figures 10, 11 and 12 show different CFD results, considering a channel partially filled with water. It is interesting to see the different liquid distributions corresponding to different input power and different wetting behaviour. In particular figure 10 refers to a the case of a relatively low input power (Q=10W) when the liquid completely wets the bottom channel. The liquid volume decrease from the condenser to the evaporator but the capillary pressure is enough to sustain liquid return avoiding dry-out. Figure 11 shows the result for a power Q=100W. In this case the liquid content at the evaporator side is less than in the previous case, but a liquid film is still present. For the same conditions if the liquid exhibit poor wetting properties (see figure 12) the condensed liquid is accumulated at the cold side and the evaporator becomes completely dry.
4. Experimental activities

Experimental investigations include the study of heat transfer performance of heat pipes using water/alcohol mixtures and different set up and configurations. These laboratory experiments specifically explore the use of self-rewetting fluids, self-rewetting brines and self-rewetting nanofluids. A number of results can be found, e.g. in [10-12].

In addition, in preparation of SELENE flight experiment, ground-based experimental activities will be carried out to identify the flight experimental liquids and concentrations, the requirements for the development of the flight hardware and the diagnostic systems. Different ground-based experiments are in progress (see figure 13). An experimental breadboard cell has been developed in order to study the preliminary configuration and setup, to identify possible problems and corresponding solutions.

In particular, ground-based experiments include stability of surface properties, material compatibility test between liquid and materials, diagnostics for evaluation of distribution of liquid and surface reconstruction (film shape and thickness measurements with interferometric techniques), concentration measurements with intrusive (optical probes) and optical techniques, such as-two-wavelength Mach-Zhender interferometer, nanofluids characterization including study of nanofluids stability, particles shape and size control.
Figure 13. Examples of experimental breadboard cells and preliminary results. The volume available for liquid is a 200mm long glass tube of inner diameter 12.5mm and outer diameter 15mm. The optical probe is 100 micron diameter. The temperature is measured with a sheated thermocouple.

5. Conclusions
The scientific requirements of SELENE ISS experiment will be defined through theoretical and numerical analyses, as well as ground-based experimental activities. The main objectives include identification of experimental liquids, requirements for the flight hardware and diagnostic systems. Current research activities include: characterization of thermophysical properties of self.rewetting fluids and nanofluids, flow visualization and interferometric analysis in relatively simple geometrical configurations to show fundamental behaviour, development of numerical tools and experiments with breadboard cells. Some of the most important results have been summarized in this article. Other experiments are in progress, including also activities dedicated to the characterization of intrusive methods for measurements of concentration and temperature profiles. Detailed theoretical and numerical studies and comparisons with experimental results will be carried out in the future. Particular attention will be focused on the heat transfer mechanisms in grooves of different shapes and size, to properly define the flight experimental configuration, also considering requirements of quantitative investigation of the liquid distributions in microchannels using optical techniques.

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