European Cooperation in the field of Scientific and Technical Research
- COST -

Secretariat

Brussels, 11 July 2006

COST 280/06

MEMORANDUM OF UNDERSTANDING

Subject :	Memorandum of Understanding (MoU) for the implementation of a European Concerted Research Action designated as COST Action P21 'Physics of Droplets'

Delegations will find attached the Memorandum of Understanding for COST Action P21 as approved by the COST Committee of Senior Officials (CSO) at its 165th meeting on 27/28 June 2006.

MEMORANDUM OF UNDERSTANDING
FOR THE IMPLEMENTATION OF A EUROPEAN CONCERTED RESEARCH ACTION DESIGNATED AS

COST ACTION P21

'Physics of Droplets'

The Signatories to this Memorandum of Understanding, declaring their common intention to participate to Concerted Action referred above and described in the 'Technical Annex to Memorandum', have reached the following understanding:

1. The Action will be carried out in accordance with the provisions of document COST 400/01 'Rules and Procedures for Implementing COST Actions', or in any new document amending or replacing it, the contents of which the Signatories are fully aware of.

2. The main objective of the Action is to improve the fundamental understanding of the physics of droplets (production, transport, coating and stock), from the microscopic scale to our macroscopic world. Fundamental information will provide tools for broad practical applications reaching from the traditional food industry to cutting-edge technologies.

3. The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at approximately 8 million EUR in 2006 prices.

4. The Memorandum of Understanding will take the effect by being signed by at least seven Signatories.

5. The Memorandum of Understanding will remain in force for a period of four years, calculated from the date of first meeting of the Management Committee, unless the duration of the Action is modified according to the provisions of the document referred to in Point 1 above.

COST ACTION P21

Physics of droplets

A. ABSTRACT

During the last five years, microfluidic technology has emerged. The applications are very fruitful in many domains: biotechnology, food science, reprographics, microelectronics and nanoscience, cleaning, cooling, tribology etc. The 'lab-on-a-chip' philosophy is given as the highest achievement that should be reached in that field of physics. A droplet of liquid is the smallest fluid entity that a microfluidic physicist has to deal with. A droplet may be considered as a fluid transport cell or even as a chemical micro-reactor. The shape and volume of the droplet have to be carefully controlled. The underlying physics is still to be discovered; volume and surface effects have the same order of importance. Basically, the internal and the surrounding micro-flows have to be well understood. This COST Action will tackle the problem by studying the droplet at the microscopic level. Both theoretical and experimental work will be performed through this Action. At the end of the Action, a theory describing the physics of the droplet will be formulated. Furthermore the collaborations will allow the development of efficient tools to create, transport, stock and transform (mixing, reacting) liquid droplets in a controlled way. Moreover the contacts made with industry will allow better responses to the technological challenge.

Keywords: droplets, interface science, microfluidic, emulsions, lab-on-a-chip.

B. BACKGROUND

Status of the problem

The physics of fluids has played an important role in the development of many areas of science from the study of blood flow in the human body to the study of macro-motion of air around the Earth. In most cases, the fluid system is a macroscopic flow (from 10^{-8} m^3/s to 10^9 m^3/s) that can be treated as a continuum. Numerous advances have been recorded both in numerical and theoretical modelling in this field.

Recent research efforts have concentrated on micro-scale flows, where the continuum approximation is not valid. The usual hydrodynamics laws break down on this molecular scale. The physics of these microsystems is very challenging as border effects and interactions between the fluid and the material it is flowing through cannot be neglected.

The practical interest for micro-flows and micro-objects has soared over the last five years. Indeed, microsystems subject to very small flows (from 10^{-12} m^3/s to 10^{-9} m^3/s) and small fluid objects (<100 µm) are at the core of many innovative applications: micro-reactors in pharmacology, chip cooling in computer science, biological chips in medicine, controlled emulsions in the food industry, detergence [1], etc. As an example, micro-droplets containing a biological material (e.g. proteins in a solvent) are of high interest in today's cutting-edge biotechnologies and fit nicely into the 'laboratory on a chip' philosophy.

The basic entity of a microfluidic system is the *droplet*. The physical properties of this liquid system are fascinating, with the dual interaction of surface and volume effects. Most applications or experiments require the accurate prediction of the evolution of a droplet size and shape and their control. Therefore, understanding the physical properties of a single droplet is the key to this research field. The influence of surface tension, of the viscosity of the liquid inside and outside the droplet, the interaction of the droplet with the substrate, the impact of a droplet on a solid are examples of the large number of experiments that can give interesting information on the underlying physics of droplets. The motion of droplets in micro-channels is considered as the emerging field of microfluidics [2].

Physical interest

Despite the familiar aspect of droplets, such objects still raise numerous fundamental questions [3]: How can a droplet form and stick onto surfaces? How does a droplet glide onto a surface? How do two droplets mix together? How can the volume of a droplet be efficiently controlled?

The complexity of such systems comes down to the fierce competition between surface effects and bulk properties. Indeed, for a droplet, interfacial forces (surface tension and Van der Waals forces) play an important role and may produce spectacular and counterintuitive phenomena, which are non-linear in nature. These effects intervene in different stages of a droplet life: the formation of droplets [4], its transport [5, 6], the coalescence of droplets [7], the impact of droplets with a target [8, 9] and the like. Indeed, droplets exhibit singularities in their shapes (cusps), displaying contact lines, bottlenecks and other peculiar patterns.

A fundamental theory describing fluids at a very low scale has yet to be elaborated. The existing theories mainly describe the behaviour of the droplet when they are on uniform and isotropic surfaces. The situation is not clear concerning Fakir-like surfaces or heterogeneous surface according to their hydrophobicity. The task is very complex and challenging. Such a theory needs to cater for the interaction of the fluid with its environment, reflecting the predominance of surface effects. In practical terms, it means that the surface chemistry of the materials has to be very well controlled. For instance, the hydrophobic/hydrophilic constitution of these surfaces should be tuned at will to obtain the expected effect on the droplet: flow, rest, mixing, etc.

Practical interest

The latest research efforts point to three major axes of development: the production and transport of droplets (droplet dynamics); the conditioning of droplets (coating, chemical composition etc.); and the creation of practical devices allowing an easy manipulation of droplets. Any major breakthrough in these topics will only come thanks to a thorough physical understanding of droplets.

The natural extension of the physics of droplets is their group behaviour: the emulsions. Emulsions are fluid dispersions composed of tiny droplets. The formation, stability and rheology of emulsions are of considerable scientific and practical interests for the food industry, cosmetics, the oil-based industry and for emulsion-based new materials [10].

Research situation

Currently, several research teams in the EU are studying the physics of droplets (spray, emulsion, the object itself, microfluidic). However, there is a lack of coordination in these efforts and there is no unified EU network devoted to this emerging field of science. Very few common publications exist (except in the same country). This European situation is in stark contrast to the significant financial support given to similar research in the USA. This COST Action is an appropriate instrument to unify these ideas and develop new physical, chemical and biological applications in Europe.

The Action

A detailed theory describing the shape and motion of a droplet is one of the principal objectives of the Action. Furthermore, droplet-manipulation tools will be invented to make the connection between experiments and applications. The control of the surface substrate is the key. Different techniques can be used such as texturing at the sub-micrometric scale by laser etching, electro-deposing hydrophobic polymers.

Amongst the list of original problems that will be investigated, fluid flows inside a moving droplet will be given particular attention, as very little is known about such complex processes, while they are probably of relevance for every single application. Another problem that will be considered concerns the coating of droplets by another fluid, also a very delicate and interesting subject. A recent study on air-coated droplets (termed 'antibubbles' [11]) has opened a fascinating range of new possibilities for liquid mixing and droplet manipulation, which the Action intends to explore further.

Conclusion

The Action based on the study of the physical properties of liquid droplets and of microfluidic elements is very promising because:

- the subject is a challenge to theoretical physics
- the subject interests a wide panel of research laboratories
- European laboratories are competitive but lack coordination
- the existing and potential applications are numerous and are the future of microfluidic technology
- the questions that have to be answered require multidisciplinary skills.

C. OBJECTIVES AND BENEFITS

The main objective of the Action is to improve the fundamental understanding of the physics of droplets (production, transport, coating and stock), from the microscopic scale to our macroscopic world. Fundamental information will provide tools for broad practical applications reaching from the traditional food industry to cutting-edge technologies.

This will be done at all relevant length scales: from the microscopic scale, with its potential applications of microfluidics, to the droplets that are part of the macroscopic world but where the physics of droplets still apply.

To begin with, the Action will tackle the physics of a single droplet. Despite its apparent simplicity, several important questions remain unanswered, such as: the production of droplets in an external fluid, observed singularities in the shape of droplets rising in a denser fluid and the wetting of droplets on micro-textured surfaces. These particular questions will be addressed theoretically, numerically and experimentally, since the Action aims at regrouping droplet specialists from those three fields. Within the framework of the Action, communication between researchers using these complementary types of investigations will foster, in stark contrast with the present situation where fruitful scientific efforts are hindered by poor connections and a lack of collaboration between experimental and numerical studies or experimental and theoretical studies.

The next level of investigation within the Action will be to design original and pertinent experiments to produce specifically engineered droplets in large quantities. Several methods will be investigated. So far, the effort has been concentrated on closed fluid circuit; the microfluidic system is composed of micro-tubes engraved in a PDMS matrix. Another interesting technique consists of texturing surface and controlling the roughness. The droplet is then manipulated on an open surface. Systems may be also conceived by taking the best of both worlds (open and closed circuits). Among the anticipated participants there is a large number of researchers with fully functioning laboratories, minimising the potential need for additional costly experimental equipment. Therefore, microfluidic elements will be designed to produce, test, mix and categorise droplets.

The Action will then move on to the study of emulsions, which are regrouping many droplets. This field is of major importance for industrial applications since emulsions are the main ingredient of a large number of products such as milks, cosmetic moisturisers and paints. However, all those industrial emulsions are strongly polydisperse (the droplets have different sizes), which makes their behaviour highly complex. The use of monodisperse emulsions obtained through microfluidics will certainly provide an interesting basis to better understand their unique properties. Two points will be specifically addressed: the study of the rheology of emulsions and their coalescence.

Finally, the Action will provide a unique opportunity to reinforce and develop existing collaborations within the industrial world. Results will dictate key requirements for various practical applications, targeting applications in industry: pharmacology, lab-on-a-chip technology, detergents, the food industry, the coating industry, etc.

D. SCIENTIFIC PROGRAMME

The following topics will be addressed:

- formation, transport and manipulation of a droplet: physical properties and study of fluid flows in a droplet
- coating and protection of a droplet
- applications and devices for microfluidics.

Each topic will be tackled from a basic standpoint while the scope for applications will also be taken into account. Indeed, efficient devices will provide accurate measurements, which will in turn lead to better descriptions of droplets and progress in microfluidic physics.

Working groups

The following working groups (WGs) will be organised. Exchanges of idea and technology will be encouraged between the WGs.

WG1: Formation, transport and manipulation of a droplet

WG1 will study the physical processes underlying the formation of droplets: from micro-droplets (µm) to macroscopic droplets (mm). This problem is crucial. The control of a small liquid volume is of importance for applications and for studying the fundamental properties of the droplets. WG1 will develop techniques for producing droplets with controlled sizes and techniques for manipulating these droplets.

Fundamental physical questions have first to be answered. The deformation and the dynamics of moving and impacting droplets will be tackled in order to approach these problems from both theoretical and numerical points of view. Moreover, the liquid flow inside the droplet is still an unresolved problem and should be relevant to any application, especially for the mixing of droplets. The modelling of micro-flows is the key to understanding the interaction of the droplet with its environment. The PIV (Particle Imaging Velocimetry) consists of spreading micro-grains that can be revealed using a laser (several anticipated participants are specialised in this kind of technique). Using a high-speed camera and correlating images, the field of the speeds is reproduced. This technique will be adapted to micro-scale fluids in order to determine how a droplet forms, how it glides on a surface, and how it mixes.

As soon as a droplet is created, the experimentalist has to be able to transport and manipulate the liquid droplet. This is not so obvious, since droplets can coalesce with each other or can wet the surface of the container. Another problem is the evaporation of the droplets. Several participating teams may join efforts to solve this problem. As far as the transport is concerned, specific surfaces have to be elaborated considering the wetting properties of the droplets and the adhesion of the liquid onto a surface. Finally, the ‘droplet handling’ topic consists of inventing tools such as optical wrenches that are able to change the shape of the droplet, to introduce another liquid in the droplet, to divide a droplet into smaller entities.

Skill and competences of the WG: surface tension, surfactant knowledge, wetting, adhesion of liquid on solid, hydrophobic and hydrophilic surfaces, motion of droplet (heat conduction, bouncing) etc.

WG2: Coating and protecting droplets

Droplets could be protected from coalescence using amphiphilic molecules but recent discoveries report that a droplet may be coated with a non-miscible fluid or even with powders. The coating of a droplet isolates the liquid from its environment. Such encapsulated droplets are very promising systems for handling droplets. Indeed, the external layer around the droplet could be fully controlled, removed, or even solidified by curing if it is composed of a cross-linkable polymer. Moreover, the coated droplet's lifetime may be tuned according to the viscosity of the coating. In so doing, a fine control of the mixing of two liquids may be reached.

The coating process of millimetre-size droplets is not well understood and the potential is still to be exploited. The research will probably be accelerated by micrometric coated droplets obtained using microfluidic devices. By extension, a group of coated droplets form an emulsion. A novel vision on this topic could emerge.

Furthermore, some recent papers report that a droplet may be coated with a gas. This particular object, termed 'antibubble', allows the separation of two liquids by a thin layer of gas. Currently, antibubbles may be obtained only in liquid containing surfactant molecules. They are giant vesicles mimicking the biological membrane of a cell. The study of thin air film is certainly of interest as far as applications are concerned: mixing, porous systems, etc.

The aim of this working group is to develop a general theory of coating through experiments with various liquids with or without surfactant. The reproducibility of these kinds of experiments is precious as soon as the mixing of two protected liquids is concerned. A lot of new applications will emerge.

Skill and competences of the WG: surfactant science, interface interaction and reaction, surface tension, droplet manipulation, emulsions.

WG3: Applications and devices

Four main challenges can be pointed out as far as applications are concerned:

1. the collision of droplets
2. the control of the mixing of two droplets of different liquids
3. the coalescence of a droplet with another liquid like catalysis
4. the exchange dynamics with fluid surrounding the droplet.

The aim of the WG is to invent and build devices that can take advantage of the droplet's physical properties to address those challenges using the results from WG1 and WG2 and sharing the experiences of the different teams.

Several methods are envisaged.

Specific polymers can be electrodeposited onto a surface. The hydrophobicity of this surface can be controlled (the properties are studied in WG1). There are polymers that can modify the hydrophobicity of the surface according to the electric field or a thermal gradient. Adaptive devices can be envisaged and a complete set of smart microfluidic devices may be created.

By laser etching or by selective chemical attack, a surface may be textured. Fakir-like surfaces are known to be superhydrophobic. By developing this technique, channels with a hydrophobicity gradient will be created. The properties of such devices are still unknown.

The goal of the working group consists in creating a device that can adapt its behaviour according to the situation through electronic microcontrollers.

Skill and competences of the WG: chip building, chemical analysis, droplet manipulation, surface control.

Meetings and workshops

The working groups will meet approximately twice a year for up to two days at a time, normally in conjunction with the meetings of the Management Committee. Depending on the generation of new results in the Action and on the general evolution of the field worldwide, workshops will be organised about once per year, and the results of the Action will be open to a scientific debate. External experts will be invited to participate. During the workshops, an open forum will be created for the benefit of all participants, internal and external to the COST community.

Technical visits and short term scientific missions

The Action will offer the participants the opportunity to visit laboratories in universities and industry where Action members are active. In addition, the Action will support Short Term Scientific Missions (STSM's), allowing researchers from participating teams to visit other participating laboratories for a period of up to one month in order to enhance scientific collaboration and to give an opportunity for common modelling and/or measuring experiments. These STSM's are clearly an important aspect of a successful Action.

E. ORGANISATION

Management and responsibilities

The Action will be administered by the Management Committee (MC). The MC will consist of a maximum of two members per COST country. The MC will meet about twice a year. The MC will elect a chairperson and a vice-chairperson from among the MC members. The chairperson and the vice-chairperson for each WG are appointed by the MC following a proposal by the WG in question.

The MC Chairperson represents the Action to external bodies; s/he is responsible for the contacts with the COST Office, and for all administrative and financial matters of the Action. S/he must prepare and deliver in time all necessary reports and documents to the Domain Committee (DC) in the field of Materials, Physical and Nanosciences and the COST Office.

Technical information exchange among the participants in the working groups will heavily rely on e-mail

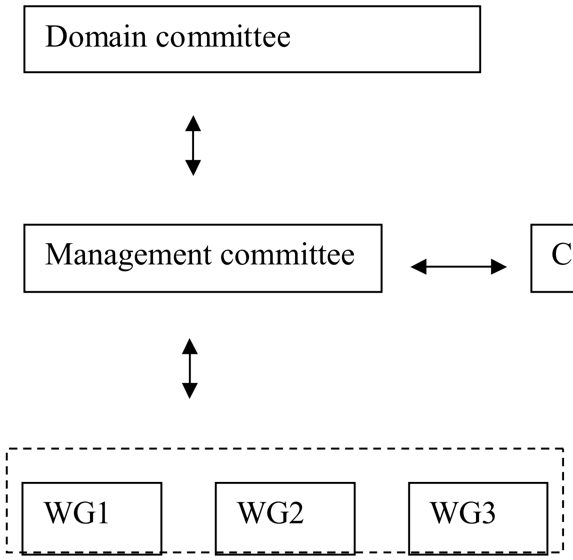

Figure 1. Organisational chart.

Reviews and reports

The Action will be open to evaluation and review of its work. Once a year, the MC chairperson will present the annual report to the DC in an oral presentation. If external experts are appointed by the DC to evaluate the Action, the MC and the WGs will deliver all documents showing the achieved results. A final report will be prepared at the end of the Action and the possibility of publishing a book, or a review article, on the results will be considered. A web site will be established for hosting all documents.

F. TIMETABLE

The Action will last four years; A tentative timetable is shown in Figure 2.

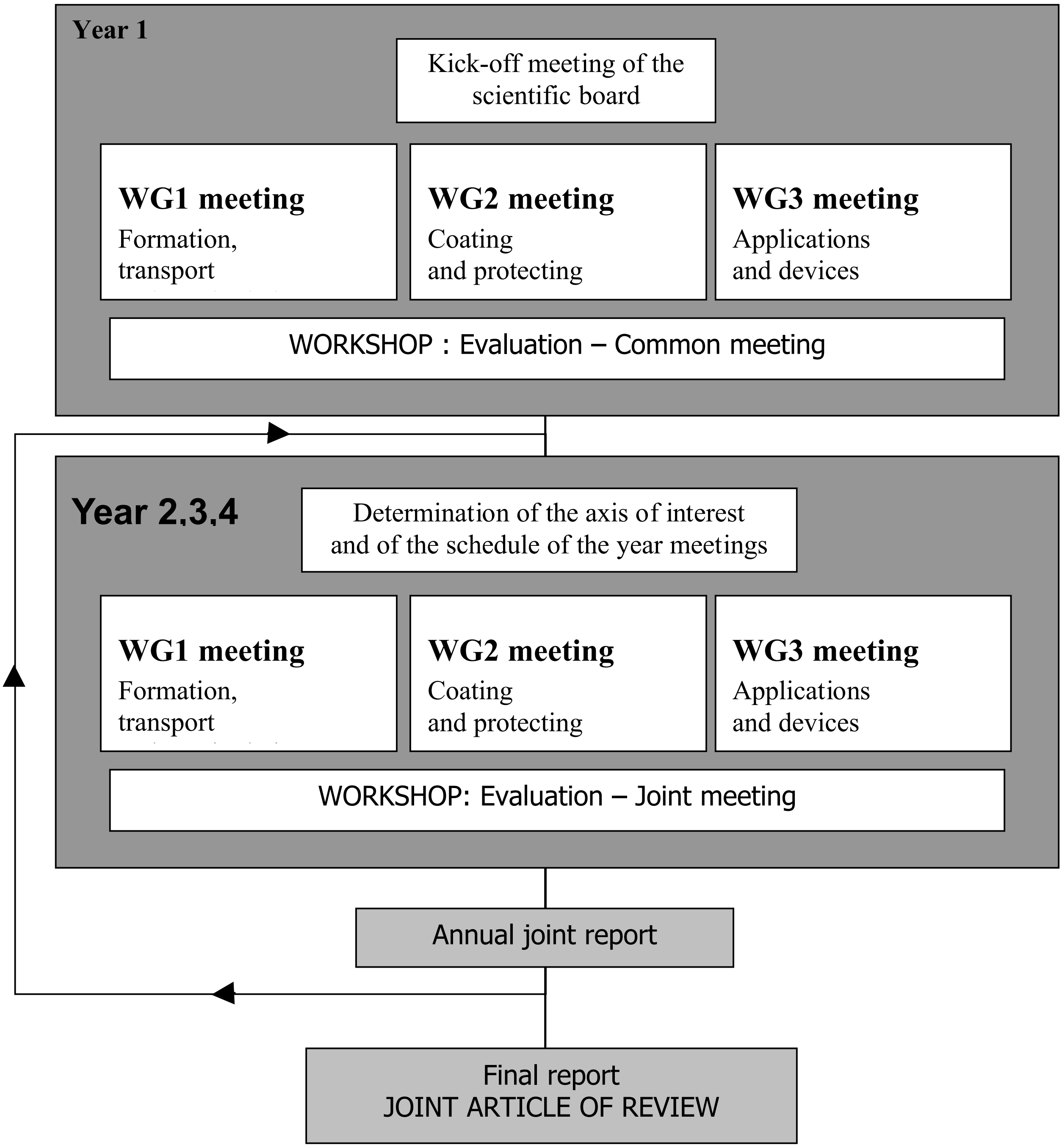

Figure 2. Timetable for the Action.

Each WG will meet during the first half of each year.

A principal workshop including the three WGs will be held in October-November of each year.

G. ECONOMIC DIMENSION

The following 15 COST countries have indicated their interest: Austria, Belgium, Bulgaria, France, Germany, Greece, Ireland, Italy, Netherlands, Poland, Romania, Slovenia, Spain, Turkey, United Kingdom and Israel (cooperating country).

The economic dimension of the activities to be carried out under the Action has been estimated to be approximately 8 million. EUR This estimate is valid on the assumption that all countries mentioned above but no other countries will participate in the Action. Any departure from this will change the total costs accordingly.

H. DISSEMINATION PLAN

The activity will benefit from the electronic interchange media. The main results of the common work will be published in peer-reviewed scientific journals, presented in conferences and workshops, and will be available on an Internet site, which will contain also all the major information on the goal of the Action and the list of the institutions involved in the Action itself. The already excellent collaboration with leading industries in the field will continue.

Therefore, dissemination will be organised by:

- Posting of general information on a public web site
- Establishment of an e-mail network
- Publications
- Proceedings
- Workshops
- A joint annual report
- A joint article of review concerning the physics of droplets.