1. Excellence

1.1. Quality and credibility of the research/innovation project; level of novelty, appropriate consideration of inter/multidisciplinary and gender aspects

Introduction

Microparticles (MPs) are important in biological, industrial and natural flows. In biological flows, different types of MPs in the form of cells, microorganisms and plasma components are constantly flowing in high concentrations through confined spaces, such as blood vessels and the lymph system[1]. For medicinal applications, designed MPs are used for drug delivery and are actively introduced to the body orally[2] or through the blood stream.[3]

MPs are extensively used in cleaning products and personal care products such as skin cleaners and toothpastes.[4] After use, these synthetic non-biodegradable MPs are washed off to the sewage and due to their small size, they pass-through water treatment systems. From there, these MPs penetrate the water cycle and are increasingly accumulating in the environment.[5] Other harmful synthetic MPs reach the environment through different paths such as emissions from burning of fossil fuels, degradation of plastic debris in the oceans[6] and microfibers (MFs) emitted from the textile industry.[7] All of these are added to the natural load of environmental MPs such as dust and microorganisms. Natural and synthetic **MPs** pose a direct **risk for human health** since they are constantly being **exchanged through water and air flows** between the environment and the human body via ingestion and inhalation.[8]

Due to their high prevalence in diverse flow regimes, it is crucial to understand the **mutual and fundamental interaction between MPs and different fluids**, especially non-Newtonian fluids which are common in biological and industrial flows. The presence of MPs in high concentrations affects the flow properties, which in turn dictates the distribution and accumulation of MPs in certain regions of the flow. A deeper understanding of these processes will assist in predicting the behavior of particles in flows and will contribute to the improvement of numerous important applications. A few examples are: **medicinal** drug delivery and point-of-care diagnostics,[9] **experimental instruments** for applied physical, chemical and biological investigations, lab-on-a-chip, microreactors, cell sorting flow cytometers[10] and different **environmental detection** techniques.[11]

There are several factors that influence the interactions between MPs and flows; for example, the generation of secondary flows around MPs due to their rotation[12] leads to local changes in the flow field that affect larger structures. These interactions may lead to turbulence attenuation by altering the turbulent regeneration mechanisms, dampening of vortices and drag reduction.[12-14] Another type of interaction involves the effect of the flow field and fluid properties on the MPs causing them to migrate to favorable positions. For example, an inhomogeneous distribution of MPs can be seen in natural flows of cloud vortices, which influences the processes that lead to raindrop formation.[15]

The important factors that influence particle-flow interactions are the fluid properties (density, viscosity, elasticity), flow confinement or geometry and particle properties (size, shape, density, flexibility). All of these factors will determine the degree of interaction between a particle and the underlying flow, which is commonly described by the non-dimensional Stokes number ($St = t_0 U/w$ where t_0 is the time scale of the particle, U is the average flow velocity and w is the characteristic length scale of the flow). Neutrally buoyant MPs with $\boldsymbol{St \sim 1}$, under **laminar flow conditions**, will migrate across streamlines due to inertial lift forces.[16] MPs migration across streamlines is enhanced, due to their intrinsic non-linearity, in inertio-elastic[17] and viscoelastic fluids.[18,19] MPs with $\boldsymbol{St > 1}$ and heavier than the fluid will accumulate in regions where the strain rate dominates over the vorticity, **outside vortex cores**, while MPs with $\boldsymbol{St < 1}$ and lighter than the fluid tend to accumulate in regions of intense vorticity, **within the vortex core**, as seen in inertial,[20,21] inertioelastic[22] and viscoelastic[23] **turbulent flows**.

Using microfluidics, different active or passive techniques for MPs sorting and removal from flows have been developed. Active sorting techniques use external force fields which are often energy costly (i.e. optical, magnetic, acoustic). Passive techniques involve the interactions between the flow field and the MPs without external forces. There are several passive sorting techniques that are based on particle manipulation by the flow field and the flow geometry, however, they often involve complicated flow patterns and convoluted micro-structures within the channels (i.e. Dean flow fractionation, micro multi-vortex manipulation, micro hydro-cyclones etc.).[24]

Since the nature of the flow field is a crucial factor for MPs distribution, it is important to study the effects of **different flow scales and flow regimes**. Nevertheless, the different studies performed to date mainly focus on **laminar or fully turbulent flows** and **intermediate flow regimes have not been often considered**. **Vortices** are not only a main building block of turbulent flows, but also characterize the flow regimes common in different configurations (for example, vortices that form in the heart, veins intersections, microfluidic intersections and around obstacles, vortices in the trails of airplanes and small winged creatures etc.). Due to the unstable and intermittent nature of vortices it is challenging to create and study them under standardized and uniform conditions.

In this proposal I suggest employing a technique that I have developed during my PhD **to form a well-controlled stationary and three-dimensional vortex**. This **single vortex** will serve as a **simplified model** for natural vortex dominated flows and will **enable to study the dynamics and interactions of MPs within a vortex in Newtonian and non-Newtonian fluids**. To generate a well-controlled isolated vortex, a **microfluidic cross-slot**

geometry (see Fig. 1) will be used. The conditions for the onset of the vortex and its persistence have been well characterized in previous work by myself and my PhD supervisors (described under methods below), providing a **strong base to perform the proposed measurements**.[25-27]

The suggested **host, Prof. Anke Lindner** at the PMMH lab at ESPCI, has extensive experimental knowledge and is a **world-leading expert in MPs dynamics in flows**; her knowledge will complement my experimental experience with vortex flows. Additionally, **secondments are planned with Prof. Amy Shen and Dr. Simon Haward at OIST Japan**, who are highly **experienced in microfluidic measurement techniques** and have done extensive research with the **cross-slot geometry** I propose to use here. The experimental work will be supported by interface-resolved **numerical simulations** in collaboration with the group of **Prof. Luca Brandt at KTH, Sweden**. The simulations are expected to capture aspects that are not accessible experimentally such as the flow field close to the particle and to control the particle properties (see further details about collaborators in sections 1.2. and 1.3.).

The findings from this study will be **significant across disciplines**, providing fundamental contributions to the knowledge about MPs – flow interactions in a simplified vortex flow field, **improving techniques** for particle sorting and transport with **potential applications** in **medicine** and **environmental** measurements and will provide **new insights** to turbulence attenuation mechanisms by MPs.

Methodology

Formation of an isolated streamwise vortex

Intersecting flows tend to become unstable and break the symmetry at low Reynolds numbers ($Re = \rho U w/\eta$ where ρ is the density and η is the viscosity of the fluid) resulting in the formation of vortices.[28-32] In a cross-slot geometry with a low aspect ratio ($\alpha = d/w$ where d and w are the depth and width of the geometry), a **single streamwise vortex forms around a stagnation point** at the center of the geometry for Reynolds numbers above a moderate critical value (Re_c).[25] By employing the state-of-the-art selective laser induced etching micro-fabrication technique in fused silica (Lightfab^{TM}) it is possible to fabricate a fully transparent, highly resistant cross-slot channel, that can be vertically mounted on an inverted microscope (Fig. 1(a)). The microscope is equipped with a long working distance objective, enabling a **direct observation on the formation of a streamwise vortex** (Fig. 1(b)). The device is washable, reusable, withstands high pressure and completely transparent, allowing the observation from different planes. This fabrication technique has a promising future in the field of microfluidics as summarized in a recent review from my current research group.[33]

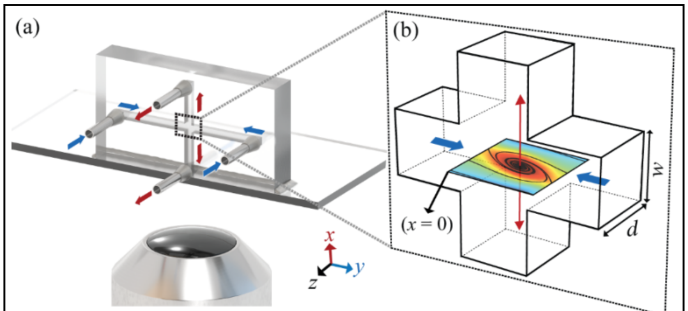

FIG. 1. (a) A schematic diagram of the experimental setup. Inflow (along *y*) and outflow (along *x*) are indicated by the blue and red arrows, respectively. (b) Schematic diagram of a vortex in the cross-slot device.[26]

During my PhD I have become a specialist in this experimental technique and performed exceptional quantitative characterization of streamwise vortex formation and its dynamics by using micro-particle imaging velocimetry (μ-PIV).[26,27] With this experimental approach, I can also control the intensity of the vortex in a highly precise and consistent manner by changing different parameters in the flow. One of the ways to **control the vortex properties** is by slight modifications of the **elasticity** of the fluid by addition of flexible polymers (4MDa *polyethyleneoxide,* PEO) in small amounts of particles per million (ppm) concentration. The polymer addition increases the relaxation time of the fluid and hence its elasticity increases ($El = (1-\beta)(\lambda\eta/\,\rho w^2)$, where β is the solvent-to-total viscosity ratio and λ is the relaxation time of the polymer). Slight changes in fluid **elasticity** may have strong effects on the flow field (Fig. 2)[27]. The experiments that I have conducted, supported by numerical simulations done by our collaborators from the group of Prof. Rob Poole (University of Liverpool, UK), have captured two main effects caused by the addition of polymer to a Newtonian solvent (dilute regime). First, the **polymer addition destabilizes the flow** and symmetry breaking occurs at lower Re_c. Second, the stretched **polymer's torque acts against the vorticity**, reducing vortex intensity.[27,34] Our findings show that a streamwise vortex will form within a narrow parameter range above a moderate Re_c. For $El \gtrsim 1$, the vortex will not form, instead, elasticity dominated instabilities take place.[35,36]

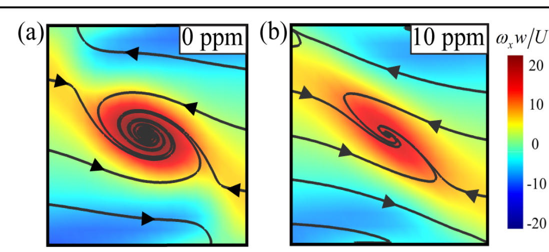

FIG. 2. μ-PIV images of normalized vorticity ($\omega_x w/U$) across the $x = 0$ plane (see Fig.1(b)) of the cross-slot geometry, scale bar: 100 μm. (a) water; (b) weakly elastic fluid, adapted from.[27]

The specific research questions (RQ) and the methodology to study the dynamics of microparticles in vortex flows:

- **RQ1 -** *How do **MPs** interact with **vortical flows** in **Newtonian fluid**?*

To address this question, I will perform a series of experiments introducing neutrally buoyant spherical particles (*polystyrene,* d_p = 20 - 240μm) in a mixture of DI-water and *glycerol*, using the cross-slot device fabricated in bulk fused silica by a 3D printer (LightFab GmbH, Germany) as described in our previous work.[24,25,32] To avoid any effects caused by the inlet bends, this microfluidic device is fabricated with straight inlets. The flow in the device will be driven by an accurate syringe pump with individual control over each inlet and outlet. A steady vortex flow field will be created by adjusting the flow rate (and *Re*). We will first investigate the interaction between the flow and a single particle, avoiding particle-particle interactions by using low concentrations of MPs. We will perform simple simulations passively tracking the particles, to reveal the trajectories, velocities and locations of the particles in the flow field. These will be compared to μ-PIV measurement of the same flow conditions with tracer particles to find the deviation of the MPs from the tracer particle behavior and possible streamline crossings.

- **RQ2 -** *How will **elasticity** of the fluid affect the **MP** distribution in **vortical flows**?*

Even a slight increase in the elasticity of the flow, by long and stretchy polymer additives in low concentrations, has strong effects on the flow field around stagnation points, such as the one that is formed at the center of the cross-slot geometry (see Fig. 2). These modifications may affect the distribution of the MPs in the flow field. Additionally, the formation of multiple stagnation points around the MP may cause polymers to stretch, leading to higher stresses close to the particle surfaces. The methodology introduced above for RQ1 will be used; in order to determine the elasticity of the fluids, we will conduct a full rheological characterization of the different non-Newtonian fluids (formed with different dilute concentrations of PEO), including relaxation times measured with an extensional rheometer (CaBER) and viscosity measured by means of a shear rheometer (Anton Paar). In collaboration with KTH group, we will perform interface-resolved numerical simulations of particles in a viscoelastic fluid to quantify the stresses due to the polymer stretching in the multiple stagnation points around the particles and their effect on the flow field. Numerical simulations will also provide information about particle rotation, enabling us to investigate how secondary flows induced by these rotations affect the interaction with the flow. The code is based on an Immersed Boundary Method to model the fluid-solid interactions, in Newtonian and viscoelastic fluids.[37]

- **RQ3 -** *How do anisotropic **MFs** interact with **vortical flows**?*

Anisotropic particles are commonly found in the environment typically as MFs.[6] The complex behavior of MFs may significantly affect the local flow field and the interactions with simple vortical flows. These affects may be enhanced by the addition of polymers to the fluid. Rigid MFs will be fabricated using a Nanoscribe 3D printer and will be tested in the steady vortex flow with Newtonian and complex fluids. As for **RQ2,** numerical simulations will resolve the additional polymeric stresses and help understanding their effect on the particle dynamics and flow field.

- **RQ4 -** *What conditions may lead to **vortex attenuation**?*

Turbulence attenuation in MPs and MFs suspensions has been previously reported,[14] yet the mechanism leading to this phenomenon is still unclear. Studying single vortex attenuation in suspension flows will simplify the problem, thus allowing us a deeper physical insight. For certain ranges of Reynolds numbers, the vortex in the cross-slot is highly stable and persistent, providing an ideal system to study vortex attenuation in complex suspensions. The effects of a systematical increase of the concentration of MPs (also of different sizes) in a steady vortex flow field will be examined in Newtonian and non-Newtonian fluids. The results will be compared with the flow field found with tracer particles and with the results of the simulations performed in collaboration with KTH.[13] The intensity of the vortex and critical conditions for vortex formation will be measured with μ-PIV. The properties of the new fluids (mixture of MPs and non-Newtonian fluids) will be measured with the rheometers to identify the differences in the relaxation times or viscosities caused by the simultaneous presence of polymers and MPs/MFs.

MPs distribution in vortical flows: Preliminary observations

During an internship at the proposed host research lab, I have conducted a series of preliminary experiments that show **first promising results** in a fully operational experimental set-up. The experiments are done in a microfluidic cross-slot channel with $\alpha = 1$. The flow is driven by 4 individually controlled neMESYS syringe pumps (Cetoni GmbH, Germany) fitted with Hamilton Gastight syringes, ensuring equal volumetric flow rates in the inlets and outlets. Neutrally buoyant spherical *polystyrene* MPs, (d_p =

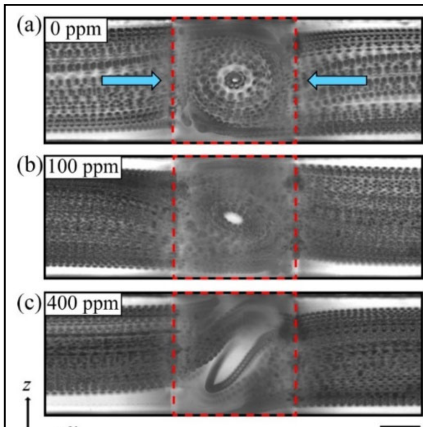

FIG. 3. Superposition of 500 images of the x = 0 plane (see Fig. 1), of a cross-slot channel. Inflow along the y direction (blue arrows). $Re \sim$ 55, scale bar: 300 μm, red dashed line marks the borders of the outflow channel. Fluids are seeded with MPs and contain: (a) 0 ppm PEO; (b) 100 ppm PEO and; (c) 400 ppm PEO.

80μm, 0.2 *wt* %) are added to the fluids (DI water-*glycerol* mixture 25 *wt*%). Images are captured with a high speed *Photron* camera at a rate of 1000 fps. A single figure is assembled from a stack of all captured images, providing an initial indication of the path of the MPs in the flow (Fig. 3). These initial observations demonstrate the **effect of weak elasticity on the flow field leading to non-homogenous distribution of MPs**.

Innovation

The innovative aspects of this proposal:

- **Unique combination of parameters and flow conditions -** With a single device it is possible to tune inertia and elasticity and control vortex onset and intensity in the flow field. The flow can be adjusted to be stable and symmetric, asymmetric steady vortex flow or unsteady periodic vortex flow. While the channel will remain the same, the particle size will be changed allowing to study a wide range of Stokes numbers.
- **Bridging over literature gaps and scientific fields -** There is broad literature coverage about suspensions in laminar shear flows and turbulent flows (mainly in 2D simulations). However, **the intermediate state of a single vortex flow** is not simple to study due to its unstable character. The proposed study will focus on fundamental aspects of MPs in vortex flows and thus will **contribute to medicinal, environmental and industrial applications** based on MP flows within confined spaces.

1.2. Quality and appropriateness of the training and of the two-way transfer of knowledge between the researcher and the host

There is a great potential for transfer of knowledge through complementary skills between me, the host laboratory at the PMMH lab in ESPCI and our collaborators at KTH, Sweden and OIST, Japan. A post-doctoral stay under Prof. Anke Lindner supervision will be a great opportunity to acquire new knowledge and produce an international and interdisciplinary study.

I will share with the host lab my experience and training with the flow in intersecting geometries of inertial and inertioelastic fluids. My experience includes μ-PIV measurements, image & data analysis, inertial flows in microfluidic channels, rheological characterization of weakly elastic fluids and extensional rheology (such as the slow retraction method which enables to measure relaxation times of weakly elastic fluids). Additionally, I can share with the host group my experience and knowledge in environmental topics which I have studied during my BSc and MSc which may lead to new ideas for future research. See also section 1.4. and my CV.

The host, Prof. Lindner and her group members are world leaders on the study of complex fluids, soft matter and suspension flows, with a **special expertise on anisotropic particles** and their complex behavior in low Reynolds number flows. I expect to learn considerably from the group about the methods, measurements techniques and theory in the field. **Unique facilities** such as the Nanoscribe, which the host group use for fabrication of MFs,[38] are available with free access in the nearby institute of microfluidics (clean rooms, microfabrication) which operates in close collaboration with ESPCI. The group has recently performed detailed studies on the complex characterization of **fiber deformation under flow**.[39] Additionally, Prof. Lindner and her close collaborator Prof. du Roure recently wrote a review on the **interactions of flexible fibers with flows**.[40] The PMMH lab is a diverse lab that houses many international experts in the field of fluid dynamics and heterogeneous systems. The weekly internal departmental meetings and weekly external seminars will keep me up-to-date with the developments in the field.

Our **collaboration with Prof. Brandt at KTH** who is an expert on **numerical simulations** of particles in flows will provide additional information not easily available from experiments, such as resolving the small scales of the flow field around the MPs and controlling parameters that are not possible to control experimentally. Findings from the numerical simulations will support experimental results and will contribute to the interpretation of the results.

Secondments with Prof. Amy Shen and Dr. Simon Haward from OIST, who have extensive experience with the cross-slot geometry, microfluidics and rheology will provide additional **support to the experimental portion** and will give access to additional experimental equipment according to the needs (such as access to the Lightfab 3D printer and advanced μ-PIV systems available at OIST).

Training through research with the objective of becoming an independent researcher:

- I will receive access to local and **international networks and conferences** organized by the host institution which will be essential to my personal advancement and to my future career in Europe (during 2018 there were 55 international visiting scientists at ESPCI).
- There are many mentorships programs in the PMMH lab in which I will actively take part and will **mentor and supervise student interns** from ESPCI and Sorbonne university.
- Diverse courses are offered for PhD students and Post-docs in the nearby universities ESPCI belongs to the larger organization PSL Research University. The courses offered by PSL are in English and cover topics related to scientific writing, IPR, grant writing and communication skills.

- High level **planning** will help me to keep track on the advancement and act quickly if any delays occur.
- I plan to initiate **outreach activities** through social media and attract young and international scientists. Additionally, I will participate in the diverse outreach programs in which ESPCI and PMMH are involved with the support of **ESPGG**, an outreach venue with proven impact on Parisian public. See further details in section 2.3 and on the webpage: www.espgg.org.
- I will participate in scientific events organized by the host institution, such as the annual summer school in the topic of self-assembled systems organized by Tel-Aviv university and ESPCI and PC focus, an open event for science sharing for ESPCI scientists.

1.3. Quality of the supervision and of the integration in the team/institution

The **leading scientist** of the project in the host university is **Prof. Anke Lindner** which is an **internationally acknowledged specialist in the physics of complex fluids and suspensions**. Anke Lindner has been the leader of many projects, including the ongoing PaDyFlow (particle dynamics in flow of complex suspensions) that was selected for a **consolidator ERC grant (2016-2021)**. She is also part of the **collaborative ITN project CALIPER** starting in September 2019. She closely **collaborates with industrial partners** as Michelin, Schlumberger or Sanofi and her groups benefits from **additional funding from the French National Science Foundation** or the Excellence Program of Paris University. In 2019 she has been **awarded the "Maurice Couette"** award, the annual prize of the French rheology society. Her current research group consists of 3 post-docs and 4 PhD students (with a pronounced gender balance). Former students of hers now work as research scientists at companies such as "Total", "Arkema" and small start-up companies as "DNA script" and "Aratinga Bio". Many of them pursue a career in academia and hold positions as assistant professors at Montpellier University, Sorbonne University, Perdue University or University of Dortmund. She has published 63 primary research papers, 1 book chapter and 1 patent which is currently pending. Additionally, she is **teaching graduate level courses** at Paris Diderot university in the topics of 'Rheology of Complex Fluids' and 'Macroscopic Physics and Complex Systems'. To complement her experimental research Prof. Lindner has developed **many close collaborations**, acknowledged by common publications, with theoreticians on an international level. Ongoing collaborations comprise for example Mike Shelley, Courant Institute, and Simons Foundation New York, USA, David Saintillan (UCSD, USA), Howard Stone, Princeton University, USA and François Gallaire, EPFL, Switzerland.

Prof. Lindner and I will meet on a regular weekly basis (or more frequently if needed) to carefully follow the experimental advancement and **to discuss the research findings and their implications**. Additionally, during our weekly meetings we will **discuss about career development** options, potential **networking** and **collaborations** possibilities (see also section 2.3.). My personal career plan will be discussed and updated every 4 months as indicated under "management" in the Gantt chart in section 3.1. The ESPCI and the PMMH lab, have extensive experience in training early career and advanced level researchers. The weekly diverse seminars, journal clubs and informal discussions and meetings at the PMMH lab will contribute to training by participation in cutting edge research. Seminars are given at the PMMH laboratory on a weekly basis by internal and external often international speakers. ESPCI hold regular seminars organized by the Industrial relations department of the *Dean of Studies for ESPCI Engineer students* and give special opportunity to meet and discuss with industry professionals to learn about research and development and career opportunities in the company. Legal and practical support is offered by ESPCI with aspects concerning the international mobility of researchers.

International collaborators for this proposal:

- **Prof. Luca Brandt** (Royal Institute of Technology, Stockholm, Sweden) is a leading specialist in computational fluid mechanics and complex fluids, such as particle and droplet suspensions and biological flows. Prof. Brandt also received an ERC Consolidator Grant, to study particle suspensions in Newtonian and viscoelastic fluids. Prof. Brandt has published over 130 peer reviewed papers and 1 book chapter on numerical methods for multiphase flows.
- **Prof. Amy Shen** (Okinawa Institute of Science and Technology) is a leading expert in the field of complex fluids and microfluidics with applications in biotechnology and nanotechnology. Prof. Shen has published over 125 peer reviewed papers, 2 book chapters and 6 patents.
- **Dr. Simon Haward** (Okinawa Institute of Science and Technology) is a well-known expert in rheological and microfluidic methods and their applications. Dr. Haward work is focused on macromolecular dynamics in highly deforming, stretching flow fields, and relating the results to real-world problems such as polymer processing, fiber spinning, ink-jet printing, enhanced oil recovery and biophysics. Dr. Haward has published over 50 peer reviewed papers, and 1 book chapter.

1.4. Potential of the researcher to reach or re-enforce professional maturity/independence during the fellowship

The proposed research topic and the goals match well with my experience and will help to further develop my career. At the host lab I will be able to combine **interdisciplinary and internationally acquired scientific knowledge** and experience from my past studies. I will be able to implement important skills that I previously gained, such as quick adaptation to new work environments and learning to **use new methods**, efficient time management and focus on the important specific goals that will lead to achieve the objectives of the project.

During my PhD at the research group of Prof. Amy Shen at OIST, I am co-supervised by Dr. Simon Haward, both are world known experts in microfluidics and rheology. Although my background was not in fluid dynamics, I quickly bridged over the gap and learned the methods and theories in the field. My research focus on *flow instabilities in intersecting geometries* in Newtonian and non-Newtonian fluids including low to moderate Reynolds numbers, which require different experimental approaches. I have gained expertise with μ-PIV, *extensional capillary breakup rheometer* (CaBER), *shear rheometer* (Anton Paar), *confocal microscope* and methods for high speed imaging. Additionally, I familiarized myself with different software for image processing and data analysis such as *Adobe illustrator*, *Techplot*, *Solidworks* and *Matlab*. I have **won the DC1 *Japanese Society for the promotion of science* (JSPS) 3 years fellowship** which also awards me with a ***KAKENHI grant*** that I independently manage and use for purchase of small equipment and for conference traveling. The JSPS fellowship supports international collaborations and hence, I was able to take an internship at the PMMH lab at ESPCI with Prof. Anke Lindner. At the PMMH lab I have performed initial measurements with suspensions and familiarized myself with the literature and methods in the field. I have published 8 papers in international peer reviewed journals (4 publications during the PhD), 5 of which are first-author papers and 3 as a co-author (additional papers are in preparation). Notably, my work on "*inertioelastic flow instability at a stagnation point"* was published in the high impact general physics journal *Physical Review X*. Additional information is given in my CV (section 4).

2. Impact

2.1. Enhancing the future career prospects of the researcher after the fellowship

I aim to become a researcher in the academia and to advance fundamental knowledge, with new discoveries by **addressing important environmental problems within the field of fluid dynamics**. The unique research domain that I propose to study requires a very specific interdisciplinary set of skills and will contribute to develop the field of fundamental fluid dynamic with focus on environmental applications. The project will help me to develop specific skills and connections that will benefit European science in the future. The relation between ESPCI, OIST, KTH and other potential collaborators will continue after the end of the project. The discoveries from this work will lead to further ideas and research directions which I am interested in pursuing in the future. Moreover, I would like to keep working in Europe and after the end of this project, I consider for applying to an ERC Starting grant.

Specifically, the proposed project and the scientific training that I will receive in the PMMH lab at ESPCI will push me to reach my goals in several aspects:

- Improve my technical skills and knowledge in specific methods in fluid dynamics and study of suspensions.
- Gain communication skills in a multidisciplinary environment of both experimental and numerical approaches.
- Learn how to efficiently manage a large-scale project.
- Add high quality publications to my resume and attend international conferences.
- Increase my chances to find future independent positions through networking and connections with senior world known scientists in the field of fluid dynamics and heterogeneous systems.
- Help me to mature and define specific goals, such as finding a future European university in which I will continue to develop.
- Through working with Prof. Lindner, I will have an excellent example on leading a research group and I will learn how to build an independent and successful academic career.
- The new conceptual approach combined with state of the art experimental set up and the support of internationally acknowledged experts gives an advantage for me to become a leading expert in this interdisciplinary research niche within Europe and outside it.

2.2. Quality of the proposed measures to exploit and disseminate the project results

Results obtained in the project on the behavior of particles in micro flows is beneficial for the scientific community in medicinal applications, **designing experimental instruments**, such as lab-on-a-chip, microreactors, cell sorting flow cytometers and environmental sampling and analysis. Particle sorting with the centrifugal approach can be **applied for chemical and biological investigations**. The data that will be obtained with non-Newtonian fluid may further increase the efficiency of such devices with relevance for non-Newtonian biological flows. Additionally, the results that will be obtained for studying vortex attenuation by suspensions may be beneficial for understanding turbulence attenuation and drag reduction mechanisms in pipe flows. This study may also have **important**

contributions in biomedical applications such as point-of-care diagnostics and intersecting flows of biological fluids inside the body which contain particulate matter (e.g. blood vessels, lymph system, etc.).

The expected impact from this study will **benefit the environment and the wellbeing of the society** with possible **applications in sampling and analysis of microplastic particles** from water resources. This research will assist in **promoting awareness** and solutions to the problems of microparticle pollution that affects natural resources (sea and oceans), human health and may also affect the water cycle and climate through exchange of particles between ocean and atmosphere. These important issues are discussed in the European Strategy Plan in the Horizon 2020 program, Pillar 2 - *Global Challenges and Industrial Competitiveness* (see "*Impact Assessment of the 9th EU Framework Program for Research and Innovation*" - Page 45 - Climate, Energy and Mobility, and Food and Natural Resources). Intellectual property obtained in this project will be protected according to the standards of the host institution. Due to the fundamental nature of the project, no patentable results are expected. Dissemination of research results to the scientific community will be done on a regular **basis ensuring open access high impact scientific research journals**. I will **deposit the research data** on a research data repository (such as arXiv). Additionally, I will share my results through conferences, summer schools and seminars, detailed in the table below and the work packages in section 3.1.:

Action's title	Expected date	Target public	ways of dissemination	Open access
Publications in scientific journals	Month 10, 20 & 24 of project	Scientific community of fluid mechanics/ colloids	Publications in open access journals	Yes
Summer school	Sep' 2021	Self-organization and self-assembled / systems	Oral / poster presentation	
Conferences				
ICR (Brazil)	Aug' 2020	International Congress on rheology	Presentation	
AERC (Spain)	Apr' 2021	European society of rheology	Presentation	
APS-DFD (USA)	Nov' 2021	General fluid dynamics meeting	Presentation	
Seminars				
KTH	Month 8 of project		Presentation	
OIST	Month 15 of project		Presentation	
PMMH ESPCI	Month 21 of project	PMMH lab at ESPCI	Presentation	

2.3. Quality of the proposed measures to communicate the project activities to different target audiences

To improve the public interest and understanding of science, the research activities of this proposal will be **communicated to the society at large**, in a way that is **accessible to non-specialists**. Special attention will be given towards communication with high school teachers and students through social media and for encouragement in scientific studies, especially among girls. This will be done in two levels, I will post videos and simplified explanations about my scientific advancements and about the life as a scientist who is also a mother. My experiments are visually striking, and I can share plenty of videos showing special vortex flows. Public engagements through this project will contribute to rise the interest in scientific studies through different levels of the educational systems, for both male and female students. Additionally, communication toward disabled students will be considered to promote their integration into scientific studies. I will join to activities such as "Researcher Night" organized by ESPGG, an organization associated with ESPCI who organizes outreach activities and offer training for researchers to perform these activities. Every year, ESPGG organizes 20 conferences and screenings, 4 exhibitions, 150 visiting classes, 250 animation sessions in schools, 120 events for the general public, 20 trainings and workshops for pros / living labs, 100 engaged researchers, 12,000 visits. Since 2011, ESPGG has been involved in 10 European projects about science communication or science in society, and around 100 partnerships. ESPGG is run by Association TRACES, a dedicated non-profit association, recognized at international level.
The specific activities I plan to contribute to are detailed in the table below:

Action's title	Action short description	Expected date and duration	Target public	Means of dissemination	Level of dissemination	Expected impact
Science web page	Regular updates and pictures will be uploaded showing scientific concepts	Update once a week / 2 weeks during the whole period	School / under-graduate	Social network such as Facebook / Twitter / Instagram	International	Encouraging student to peruse science
Fête de la Science	Scientific mediation to promote science	2 weeks in October	General public	Exhibitions and workshops	National / local	Communicating science to the public
Lab Open Days	Open doors to the public to visit the labs	February	General public	Exhibitions of experiments	Local	Communicating science to the public
Researcher Night	Researchers meeting the public	September	General public	Scientific discussion	National / local	Communicating science to the public

3. Quality and Efficiency of the Implementation

3.1. Coherence and effectiveness of the work plan, including appropriateness of the allocation of tasks and resources

The project is divided to 3 work packages according to the RQ's presented in section 1.1.

Work package number	**1**		**Start month**	**1**	**End month**	**10**
Work package title	**MPs distribution in vortex flow** (Newtonian and complex fluids) -addressing RQ1 and RQ2 (see sec. 1.1.)					
Objectives	Study MPs distribution in vortex flow of Newtonian and non-Newtonian fluids					
Description	- Perform systematical data collection of spherical MPs in vortex flows. - Vortex intensity will be changed to study the inertial and inertioelastic effect on the particles. - Perform rheological characterization of the fluids. - Set up a working experimental protocol. - Set up numerical simulations. - Writing Matlab code for data analysis including particle tracking.					
Methodology	- Spherical particles: *polystyrene* (Dynoseeds Microbeads, ρ = 1059 kg m-3) in a range of commercially available sizes (20, 40, 80, 120, 240 micrometer). - To avoid particle sedimentation, glycerol 25wt % will be added to DI water. - High molecular weight *polyethylene oxide* (4MDa) will be used to increase the elasticity of the fluid. - Tracer fluorescent particles (5 micrometer) / dye to visualize the background flow. - Data collection - High speed camera (Photron), microscope x5 magnification. - Data analysis – Matlab - data analysis with PIVlab / ImageJ. - Heat maps of particle distribution will be prepared.					
Deliverables						Month
	D1,1	Conference – SOR conference, Brazil, August 2020.				4
	D1,2	Outreach activity "Fête de la Science"				7
	D1,3	Data collection and analysis of MP in vortex flow (Newtonian and non-Newtonian)				8
	D1,4	Write a report / summarize results towards a manuscript				10
Visit collaborators	to	KTH	Start month	8	End month	8
Objectives	Establishing collaboration and initiating numerical simulations + seminar (2-3 days visit)					

Work package number	**2**		**Start month**	**8**	**End month**	**20**
Work package title	**Anisotropic MFs distribution in vortex flow** - addressing RQ3 (see sec. 1.1.)					
Objectives	- Fabrication of rigid fiber-like particles. - Collect data with fiber-like particles with Newtonian and non-Newtonian fluids. - Find the optimal experimental conditions for visualization of fiber behavior in vortex flow (flow rates, particle volume fraction, polymer concentration) - Adjust Matlab code to analyze fibers.					
Description	- Fiber like particles will be fabricated using a Nanoscribe 3D printer[35]. - Data collection with anisotropic particles. - Experiments with Newtonian fluid. - Non-Newtonian fluid – dilute regime polymer solution.					
Methodology	- Fluids – Newtonian fluid. - Tracer fluorescent particles (5 micrometer) / dye to visualize the background flow. - Data collection - High speed camera (*Photron*), microscope x5 magnification. - Data analysis – Matlab - data analysis with PIVlab / ImageJ					
Deliverables						Month
	D2,1	Outreach activity - Lab Open Days				10
	D2,2	Fabrication of MF				12
	D2,3	Conference – AERC, Spain, April 2021				12
	D2,4	Data collection and analysis of fiber-like particles in vortex flow				14
	D2,5	Outreach activity "researchers' night"				17
	D2,6	Write a report / summarize results towards a manuscript				20
Secondments	to	OIST	Start month	15	End month	15
Objectives	Complementary experiments with µ-PIV + Seminar (duration 2-3 weeks)					

Work package number	**3**		**Start month**	**18**	**End month**	**24**
Work package title	**Vortex attenuation by MPs -** addressing RQ4 (see sec. 1.1.)					
Objectives	- Find the experimental conditions leading to vortex attenuation.					
Description	- Study high concentration of particles to find the critical coditions in which vortex attenuation occurs.					
Methodology	- Particles - polystyrene spherical particles with diameter of 20, 40, 80, 120, 240 micrometers. - Fluids – Newtonian, non-Newtonian fluid PEO 4MDa. - Tracer fluorescent particles (5 micrometer) / dye to visualize the background flow. - Data collection - High speed camera (*Photron*), microscope x5 magnification. - Data analysis – Matlab - data analysis with PIVlab / ImageJ					
Deliverables						Month
	D3,1	Conference – APS DFD meeting USA, November 2021.				18
	D3,2	Data collection and analysis of MPs in vortex flow				22
	D3,3	Write a report / summarize results towards a manuscript				24

List of major milestones:

Mile stone	Description	Month
M1	Setting up a protocol for experiments and data analysis including a working Matlab code.	6
M2	Completing initial data analysis with conclusions on how to proceed to the next work package	8
M3	Fabrication of microfibers	12

The work plan of the project is outlined in the below GANTT Chart (April 2020 – April 2022):

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Work package 1	WP1																							
Work package 2								WP2																
Work package 3																		WP3						
Management																								
Milestone						M1		M2				M3												
Deliverable								D1,3		D1,4		D2,2		D2,4						D2,6		D3,2		D3,3
Secondment															S									
Conference				D1,1								D2,3						D3,1						
Seminar								KTH							OIST						PMMH			
Outreach							D1,2			D2,1							D2,5							

3.2. Appropriateness of the management structure and procedures, including risk management

The proposed project will be managed by the European Affairs Department of ESPCI which is fully experienced in this field with dedicated staff in legal, financial and administrative issues. ESPCI already managed ITN projects, IF fellowship and an ongoing COFUND. I will be employed with a standard short-term contract, with all standard benefits and obligations. Employment at the PMMH Laboratory will be made in conformity with the H2020 rules. In 2019, ESPCI Paris signed the endorsement letter, which allowed the school to start the implementation process of the Human Resources Strategy for Researchers (HRS4R), promoted by the European Commission. ESPCI Paris has indeed expressed its ambition to "deliver better employment and working conditions for researchers".

The ESPCI has a continuing training department which offers French courses for foreigners. At the beginning of the project, a kick-off meeting will be organized by the European Affairs Department of ESPCI involving myself, the scientist in charge, the administrative staff of the laboratory and the partner institution representative to explain the project management and reporting procedures, the rights and obligations of each and the organization of the follow up of the project. Further to the day-to-day exchanges with my team in the lab (see section 1.3), a formal meeting with the Supervisor and our collaborators (by video conference if needed) will be held every 4 months in order to assess the progress against the workplan of the project, and also to update my Personal Career Development Plan, program of Outreach and Dissemination activities, planned/modification of secondments (these meetings are shown under management in the Gantt chart in section 3.1.). The risks that might endanger reaching the project objectives and the contingency plans to be put in place are described below:

Milestone	Risk	Intensity	Contingency plan
1	Setting up a protocol for experiments and data analysis	Low	The experimental set up has been already tested with promising preliminary results. A code for data analysis will be written.
2	Completing initial data analysis with conclusions on how to proceed	Low	The conclusions from the WP1 will be directing the project and implemented in WP2 and WP3
3	Fabrication of microfibers	High	Fiber suspensions are not commercially available, and it is difficult to fabricate them in large quantities. If fabrication fails, different fiber particles such as actin fibers, fishing line,[41] or Nylon[42] will be tested.

3.3. Appropriateness of the institutional environment (infrastructure)

Host Institution:

ESPCI Paris, is located in the center of Paris, is a "Grande Ecole d'Ingénieurs" founded in 1882 by the City of Paris. There are 530 tenured professors and research scientists (including PhD and Postdoctoral students) in 11 Joint CNRS research units dedicated to both education and research located in a 200,000 m² campus. ESPCI Paris performs research at the highest international level in Physics, Physicochemistry, Chemistry and Biology, with all the infrastructure and equipment needed to tackle the physicochemical, biological, optical and engineering components of this highly interdisciplinary project is available at the institute. In addition to offering masters and PhD degrees with accredited Doctoral Schools, ESPCI Paris is strongly focused on the industrial applications of fundamental research and has one patent application each week and about 3 technology-driven startups each year. For all administrative and financial questions related to the project management, I will be assisted by the European Affairs Department of the ESPCI, which has long experience in the management of European projects. The host institution will provide all appropriate assistance to make this fellowship as smooth as possible, to give it the maximum chances for a successful outcome. Additionally, unique facilities such as the Nanoscribe 3D printer, are available with free access in the nearby institute of microfluidics (clean rooms, microfabrication) which operates in close collaboration with ESPCI. The host lab is equipped with a top-level infrastructure and instruments (described in part 5) that are essential to achieve the project goals. During my stay I will have my own personal work desk, a personal computer and online access to the library and scientific journals. Additionally, I will have access to the laboratory spaces with all necessary equipment. The ESPCI Paris also provides its employee with services and benefits from the CNAS (National Social Action Committee), services to improve the material and moral conditions of employees. The ESPCI Paris being a funder member of the PSL University, I will have access to the full scope of PSL services (student and campus services, events, sports, culture, etc). A wide range of sports are offered during the academic year. I will have access for student accommodations through the ESPCI privileged partnership with Cité Universitaire. Most of these accommodations nearby the ESPCI campus and in any case in the city of Paris allowing efficient transportation to the school. The 'Fondation Nationale Alfred Kastler' and 'Science Accueil' are two organizations that support foreign researchers with their administrative and social integration in France. The Kastler Foundation oversees coordinating the French network of Euraxess Services Centers. Services provided include assistance with administrative formalities (visa, residence card, work permit), health insurance (social security and complementary private insurance), opening of a French bank account, housing, legal assistance, language courses and cultural activities. The EU department will manage the secondment agreement with OIST and collaboration with KTH.

Secondment Institution:

The Okinawa Institute of Science and Technology Graduate University (OIST) is located in the main island of Okinawa, Japan and have an interdisciplinary graduate school offering a 5-year PhD program in Science. Over half of the faculty and students are recruited from outside Japan, and all education and research are conducted entirely in English. The OIST Graduate University conducts internationally outstanding education and research in science and technology, and thus contribute to the sustainable development of Okinawa, and promote and sustain the advancement of science and technology in Japan and throughout the world. OIST offers a flexible working environment, encouraging innovation, creativity, and adaptability; accommodate new initiatives and ensure a thoroughly interdisciplinary academic environment; The global networking at OIST includes hosting, attending, and participating in international meetings, conferences, workshops, and other events to enhance the university's visibility and increase research and education opportunities. OIST collaboration with industry by creating an environment where research outcomes are developed and applied by industry for the benefit of society, the sustained development of Okinawa, and the competitiveness of Japan. The facilities at OIST are all new and considered the state-of-the-art, providing the best environment to conduct research although it is geographically remote. OIST has an outstanding support team for relocation and visiting scientists providing all necessities.

References:

[1] Shet A. & S., *Vasc. Health Risk Manag*.; 4(4):769–774 (2008). **[2]** Mathiowitz E., *Nature*, 386:410-414 (1997). **[3]** Allen M. A., *Science*, 303,5665:1818-1822 (2004). **[4]** Zitko V. and Hanlon M., *Mar. Pollut. Bull.,* 22:41–42 (1991). **[5]** Akdogan Z. & Guven S., *Environ. Pollut.*, 254; 113011 (2019). **[6]** Antão Barboza L.G., *Marine Poll. Bull.*, 133: 336-348 (2018). **[7]** Henry B., *Sci. Total Environ.,* 652: 483-494 (2019). **[8]** Wright S.L. & Kelly F. J. *Environ. Sci. Technol.* 51, 12:6634-6647 (2017). **[9]** Vashist S.K., *Biosensors,* 7(4):62 (2017). **[10]** Safford H. R. & Bischel H. N., *Water Research*, 151:110-133 (2019). **[11]** Yew M., *Global Challenges*, 3, 1800060 (2019). **[12]** Voth G. A., & Soldati A., *Ann. Rev. Fluid Mech.*, 49:249–76 (2017). **[13]** Kazerooni T. *Phys. Rev. Fluids* 2, 084301 (2017). **[14]** Clisse M., *Phys. Fluids,* 27, 061702 (2015). **[15]** Falkovich G., *Nature*, 419: 151-154 (2002). **[16]** Di Carlo, D., *PNAS,* 104.48: 18892-18897 (2007). **[17]** Yang S., *Lab Chip,* 11: 266–273 (2011). **[18]** DAvino G. & Maffettone P.L., *J Nonnewton Fluid Mech*. 215: 80-104 (2015). **[19]** Zhou Y., *Anal. Chem.* 91, 7: 4577-4584 (2019). **[20]** Balachandar s. & Eaton K., *Ann. Rev. Fluid Mech.* 42: 111-133 (2010). **[21]** Toschi F. & Bodenschatz E., *Ann. Rev. Fluid Mech.,* 41:375-404 (2009) **[22]** Di Lillo et al., *Phys. Rev. E.,* 85, 036308 (2012). **[23]** Garg H., *Eur. Phys. J. E*, 41: 115 (2018). **[24]** Sajeesh P. & Sen A.K. *Microfluid Nanofluid,* 17: 1-52 (2014). **[25]** Haward S., *Phys. Rev. E,* 93, 031101 (2016). **[26]** Burshtein N., *Phys. Fluids*, 31, 034104 (2019). **[27]** Burshtein N., *Phys. Rev. X*, 7, 041039 (2017). **[28]** Kalashnikov V. N. & Tsiklauri M. G., *Fluid Dyn.,* 26: 161 (1991). **[29]** Ait Mouheb N., *Microfluid. Nanofluid.* 10, 1185 (2011). **[30]** Vigolo D., *Proc. Natl. Acad. Sci.* USA **111**, 4770 (2014). **[31]** Zhang J. W., *Chem. Eng. J.* 358, 1561-1573 (2019) **[32]** Zhang J. W., *Phys. Fluids,* 31, 034105 (2019). **[33]** Burshtein N., *Curr. Opin. Colloid Interface Sci.*, 43:1–14 (2019). **[34]** Zografos K., *J. Nonnewton Fluid Mech.,* 262:12-24 (2018). **[35]** Arratia P.E., *Phys. Rev. Lett.* 96, 144502 (2006). **[36]** Sousa P., *Soft Matter*, 11, 8856 (2015). **[37]** Izbassarov D., *Int. J. Numer. Meth. Fluids*, 88, 521-543 (2018).**[38]** Berthet H., *Appl. Sci.*, *6*(12), 385 (2016). **[39]** Cappello J., *Phys. Rev. Fluids,* 4: 034202 (2019). **[40]** du Roure., *Ann. Rev. Fluid mech.*, 51: 539-572 (2019). **[41]** Lopez D., et al *Phys. Rev. Fluids* 2: 024306 (2017). **[42]** Cole M., *Sci. Rep.* 6: 34519 (2016).