PROGRESS REPORT (Year 2023-24)

File No: (CRG/2021/000747)

1. Project Title: *Project Title: Investigation of Fractal Growth on the Curved Surfaces in Hele Shaw Flow*	**DST No:** *CRG/2021/000747*
2. PI (Name and Address): *Dr. Kiran Suresh Bhole,* *Associate Professor, Department of Mechanical Engg., Sardar Patel College of Engineering, Andheri (West), Mumbai 400058*	**Date of Birth:** *10.03.1977*
3. Co-PI (Name and Address): *Dr. Nilesh Raykar,* *Professor, Department of Mechanical Engg.,* *Sardar Patel College of Engineering, Andheri (West),* *Mumbai 400058*	**Date of Birth**: *19.05.1967*
4. Broad areas of Research: *Engineering Sciences*	
4.1 Sub Area: Mechanical & Manufacturing Engineering & Robotics (*Engineering Sciences)*	
5. Approved Objectives of the Proposal: Objective 1: Design and development of experimental setup for formation of control micro fractals for curved surfaces. Objective 2: To study the control of fractals on conical and spherical Hele-Shaw flow using pits and multiport. Objective 3: To develop the process plan for 3D scalable fractal structures. Objective 4: To control the development of microfractals on conical and spherical surfaces. Objective 5: Effect of rheology of nano particle filled non-Newtonian resin in fractal formation.	
Date of Start: 21st January 2022	**Total cost of Project:** Rs. 31,80,921
Date of completion: 20th January 2025	**Expenditure as on:** 03rd February 2024 Capital (Non Recurring) – Rs 2348989 General (Recurring) – Rs 383270

6. Methodology:

The proposed work includes the development of 3D micro fractals from the non-Newtonian fluid on curved surfaces. To obtain the micro fractals, dedicated experimental setup is prepared. The setup is first designed in a CAD Software based on design considerations and then is fabricated. It is then utilized for conducting experiments. High viscosity fluid is administered and squeezed between the two plates and after an interval of few seconds, moving plate is taken apart from the fixed plate linearly. Linear motion to moving plate in Z-direction is imparted by virtue of the linear actuator and Z-stage. Micro-position controller is used for managing Z-directional motion. Micro fractals are obtained on both the plates as a replica of each other. The study of micro fractals formation process is considered under the influence of various process variables such as viscosity of fluid, separation velocity, quantity filled, inclination between substrates, geometric micro indentation or protrusion on the surface. Initially, governing process variables are identified and then the same are employed for conducting design of experiments setup by different levels of the principal governing process variable. Expected outcome of design of experiments is the experimental model in terms of non-dimensional parameters which will be used to obtain controlled micro fractals by setting up the optimum levels of governing process variables. Further, employing pits or multiport (source holes) anisotropies on curved surfaces of plates, control over the micro fractal formation will be achieved. Different combinations of anisotropies can be tried for obtaining desired micro fractal formations. Thermal or

photocurable resin will be seeded by nano powder of alumina and that seeded resin used as a non-Newtonian resin. Effect of seeding of alumina nano powder in resin on fractal formation will be studied.

7. Salient Research Achievements:

7.1 Summary of Progress

The Lifting Plate Hele Shaw experimental set up capable of handling both 2D and 3D surfaces is developed. The developed set up of Lifting Plate Hele Shaw configuration (refer Figures 7 and 8) is having feature of modularity and scalability for the generation of fractals on 2D and 3D surfaces spontaneously. The data acquisition system of NI is employed to capture the process variables employed for viscous fingering. An indigenously developed software "Micro-Motion" (refer Figures 2 and 9) is suitably used to control the movement of motorized vertical stage.

(a) (b) (c) (d)

Figure 1 : Conical & Hemi-spherical plates – (a) Conical base plate (b) conical upper plate (c) Hemi-spherical base plate (d) Hemi-spherical upper plate

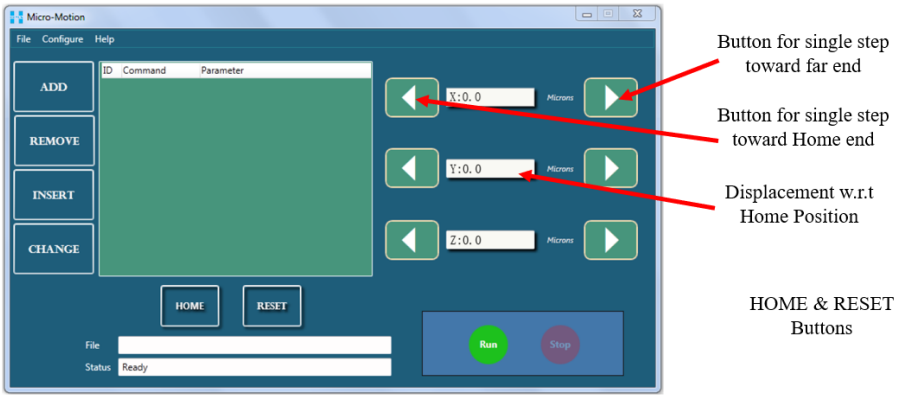
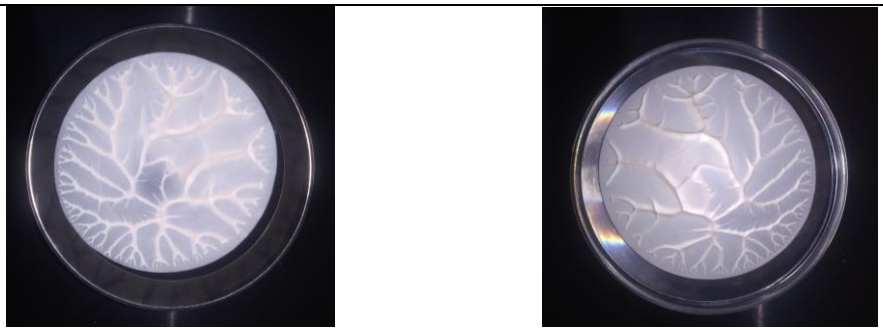


Figure 2 : Micro Motion Software GUI

Viscous Micro-fractal patterns, with varying process parameters, have been formed on 100 mm diameter conical plates (refer Figure 1). Micro-fractal patterns formed on 55° conical plates are shown in Figure 3. Different combinations of process parameters viz. gap between the plates and plate lifting velocity have been employed for the same and generalized matrix of dimensionless width (b/d) vs. Capillary number on non-dimensional scale has been developed (Figure 4).



(a) Lower Plate (b) Upper Plate

Figure 3 : Micro-fractal patterns formed on 55° conical plates

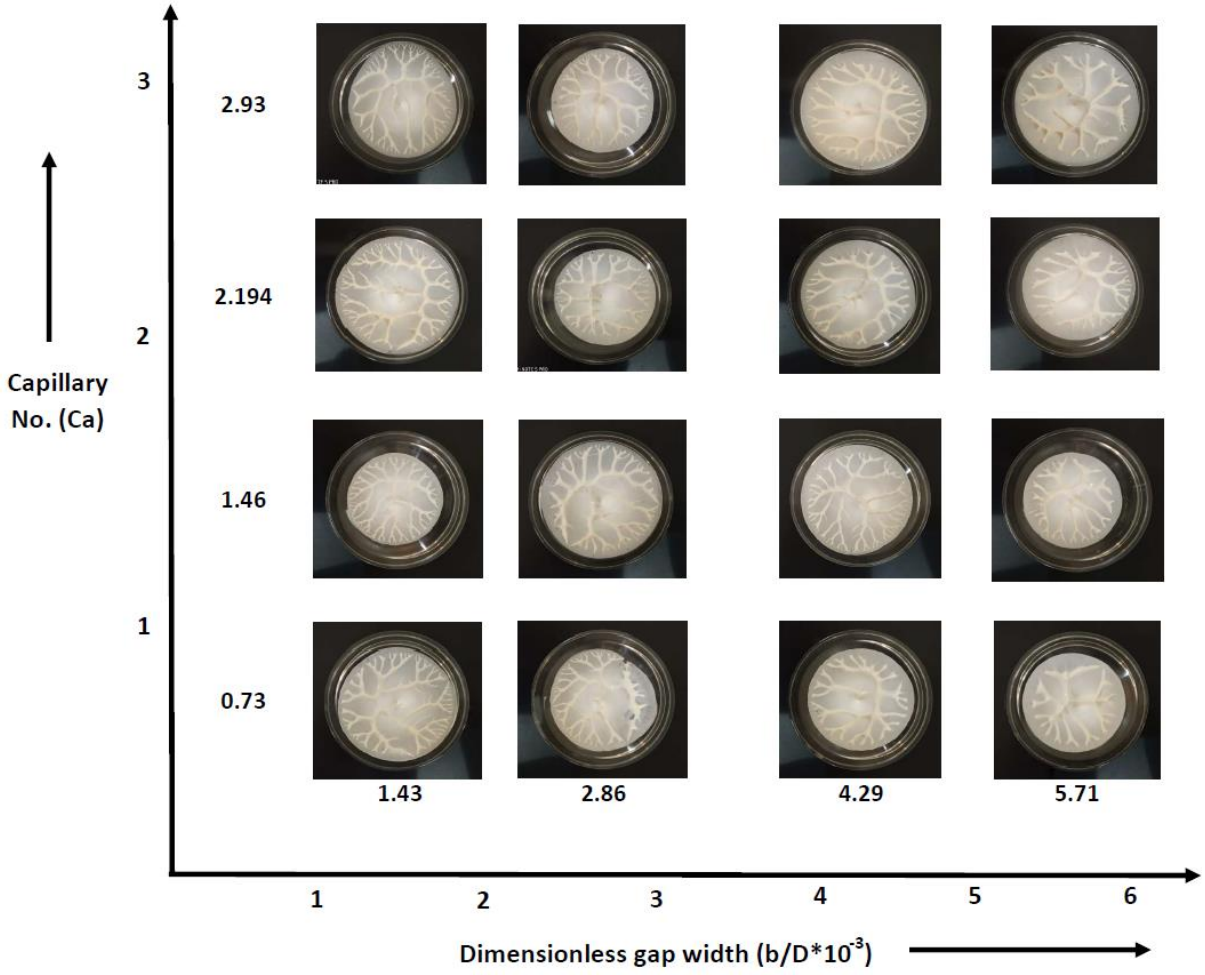


Figure 4 : Micro-fractals formed for different combinations of Ca & b/D ratio on conical plate

Experiments of micro-fractals formation on hemi-spherical plates (Figure 5 c & 3 d) have also been carried out. Comparison of micro-fractals obtained on hemi-spherical plates with those obtained on conical plates exhibits effects of change in 3D surface on viscous fingering phenomenon.

One of the critical factors in affecting the nature of viscous micro fractal patterns i.e. viscosity of fluids is also considered in the study. Effects of changing the viscosity of interacting fluids in lifting Hele-shaw cell is studied (homogeneous resin is prepared through stirrer, refer Figure 11 a). Solution of low-cost bingham plastic fluid Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride and Glycerol with different mixing

ratio is experimented in Hele-shaw cell. Table 1 shows fluids mixing ratio used in experimentation. Micro fractal patterns obtained by using the aforementioned solutions in lifting Hele-Shaw cell are shown in Figure 5. The obtained fractals are observed through microscope (refer Figure 11 b). The fractals are turned into channels through post-processing under degassing unit and functionally tested through multi-syringe unit (refer Figure 10 and 12).

Table 1: Solution with fluids mixing ratio used in the experimentation and micro fractal patterns obtained

Experimental Set	1	2	3	4	5
Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride	20gm	20gm	20gm	20gm	20gm
Glycerol	0	5gm	10gm	15gm	20gm
Images of fractal patterns formed	Fig.5.a	Fig.5.b	Fig.5.c	Fig.5.d	Fig.5.e

Figure 5: Micro fractal patterns obtained using prepared solution in lifting Hele-shaw cell

Further, impact of surface plate roughness on fractal formation using lifting plate Hele-shaw cell is also studied. This involved methodically using the Hele-Shaw Cell, utilizing a range of paper grades, and systematically conducting experiments to clarify the subtle behaviours of emerging patterns under different process parameters. Figure 6 shows fractals formed on different grade papers using lifting plate Hele-Shaw cell at lifting velocity of 2 mm/min and 0.1 mm gap between the plates.

(a) (b) (c) (d)

Figure 6: Fractals on different grade papers with 2mm/min Lifting Velocity and 0.1mm Gap between the plates (a) Craft Paper (b) Chart Paper (c) Sandpaper 1000 Grit (d) Velvet Paper

7.2 New Observations:

Micro fractal-like patterns are formed when highly viscous fluid is squeezed to specific thickness between two parallel plates and then plates are taken apart with a controlled velocity. Change in 3D surface geometry of plates affects the pattern characteristics. Fine pattern of fractals is observed in case of smooth curved surface of hemi-spherical plate in contrast with the coarse patterns formed on conical plate which has a vertex at centre. Dense micro fractal patterns with increased branching are associated with lower b/D ratio values, and vice versa. Tendency to form fractals at higher values of Ca and dimensionless gap is less and vice versa. With the rise in the Ca values, patterns density found shifting towards periphery. In contrast, b/D ratio has a significant influence on fractals. With rising b/D ratio, thickness of fractal branches found increasing. Number of branches is also has decreasing trend with higher b/D ratios. Alterations in the high viscosity fluid used in micro fractal formation, have shown corresponding changes in its viscosity, and hence in fractal patterns formed from the same. Higher percentage of Glycerol in the Sodium; 5-chloro-2-(2,4-dichloro-phenoxy) phenol; fluoride solution leads to proportionate increase in the viscosity of fluid solution and significant changes in patterns thus formed.

7.3 Innovations:

- Development of fractal-like net-shaped micro-structures by a novel lithography-less method that takes place spontaneously.
- Designed and developed experimental setup can be used for the development of net-shaped micro-structures on plane (flat) as well as curved surfaces and also 3D surfaces. Precise control over process parameters utilized in the fractal formation can be achieved.
- Variations in the net-shaped micro-structures by adding innovative dimension of surface roughness in the study.

7.4 Application Potential:

7.4.1 Long Term:

- Development of micro-mixing application utilizing multi-staged, multi-branched micro channels by systematic administration of fluids for mixing.
- Design and synthesis of artificial leaf from developed net shaped fractals.
- Heat Exchanger design and development for effective mixing of fluids with dissipation of heat content.

7.4.2 Immediate:

- Utilization of PDMS mould of net-shaped micro fractals formed on conical, hemi-spherical and other 3D surfaces for micro-mixing applications.

7.5 Any other

Paper entitled “Anisotropic Approach to Control Viscous Fingering Pattern Generated in

Lifting Plate Hele-Shaw Cell" was presented in the ASME IDETC/CIE 2022 conference held at St. Louis, USA during August 14 – 17, 2022. **The paper presented received the "Best Paper Award" in Micro and Nano Systems track in this prestigious ASME IDETC/CIE 2022 conference (certificate is attached at the end of the report).** The travel grant for attending the conference was supported by SERB through ITS scheme (File Number: ITS_2022_001117). Investigators would like to thank SERB for support provided. The generous funding from SERB is acknowledged in all the papers published on the work as outcome of the project. (refer Figure 13 for the ASME best paper award certificate)

Research work which remains to be done under project:

- Planning and execution of generalized method for introducing anisotropies on the 3D plate surface for obtaining net-shaped structures on 3D surfaces.
- Process plan for PDMS molds for the 3D net-shaped patterns is to be articulated. Alternative resins for the mold formation is planned for investigation.
- Alternative process to develop the mold from the fractals generated on the lateral curved surfaces.

Ph.D Produced No: 05 (02 completed, 03 in progress)

Technical Personnel Trained = 21

Research Publications arising out of the present project: 5

List of Publications from this Project (including title, author(s), journals & year(s):

(A) Papers published only in cited Journals (SCI):

1. Kale, B., Bhole, K. S., Raykar, N., Sharma, C., Deshmukh, P., & Oak, S. (2022). Fabrication of meso sized structures through controlled viscous fingering in Lifting Plate Hele-Shaw Cell with holes and slots. Advances in Materials and Processing Technologies, 1-20. https://doi.org/10.1080/2374068X.2022.2127985
2. Kale, B. S., Bhole, K. S., Dhongadi, H., Oak, S., Deshmukh, P., Oza, A., & Ramesh, R. (2022). Effect of polygonal surfaces on development of viscous fingering in lifting plate Hele-Shaw cell. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-8. https://doi.org/10.1007/s12008-022-01030-9
3. S. Oak, K. Bhole, B. Kale, H. Dhongadi (2023). Experimental characterization of spontaneous formation of micro-fractals on conical surfaces in Hele-Shaw cell. International Journal on Interactive Design and Manufacturing (IJIDeM), https://doi.org/10.1007/s12008-023-01260-5

(B) Papers published in Conference Proceedings, Popular Journals etc.

1. Bhole, KS, Kale, BS, Mastud, S, Raykar, N, Sharma, C, & Deshmukh, P. "Anisotropic Approach to Control Viscous Fingering Pattern Generated in Lifting Plate Hele-Shaw Cell." Proceedings of the ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 8: 16th International Conference on Micro- and Nanosystems (MNS). St. Louis, Missouri, USA. August 14–17, 2022. V008T08A004. ASME. **[Received Best Paper Award in ASME IDETC 2022 Conference at St. Louis, USA]** https://doi.org/10.1115/DETC2022-89600
2. Kiran Suresh Bhole, Bharatbhushan Kale, Dipali Bhole, Sachin Oak. Design Methodology for Development of Experimental Setup for Fabrication of Controlled Micro and Meso Fractals, Procedia CIRP, Volume 119, 2023, Pages 501-507, ISSN 2212-8271. https://doi.org/10.1016/j.procir.2023.03.112.

Patents filed: 01 Design Registration and 01 Utility Patent Filed

Title: Experimental Setup for Study of fractal formation on Curved (Conical, Spherical) Surfaces in Lifting Plate Hele-Shaw Flow

Applicants: Bharatbhushan Kale, Chetna Sharma and Kiran S. Bhole

Design Registration Number 340352-001

Institute/Organization: Sardar Patel College of Engineering, Andheri Mumbai.

Title: Machine for the Development of 2-D and 3-D Microfracatals through Lifting Plate Hele-Shaw Cell

Applicants: Kiran Suresh Bhole, Bharatbhushan Kale, Amol L. Mangrulkar

Indian patent application number 202321081635

Institute/Organization: Sardar Patel College of Engineering, Andheri Mumbai.

Major Equipment (Model and Make)

Sr. No	Sanctioned List	Procured (Yes/No) Model and Make	Cost (In Rs)	Working (Yes/No)	Utilization Rate (%)
01	Data Acquisition System	Yes, cDAQ-9178, NI9213, NI9940, NI9229, NI9971, ETC. Make: NI system	1067645	Yes	50%
02	Motorized Linear Translation Stage, Stepper Motor	Yes, Model: LMS 150150-3, MVTS-125125-100 Make: Holmarc	710957	Yes	100%
03	Benchtop Stepper Motor Controllers (Three Channel)	Yes, Model: LMS 200 200 -3, Make: Holmarc	130942	Yes	50%
04	Power Supply	Yes, 0-32 V DC, 0-10A, SVL032010, Make: Sairush	40828	Yes	100%
05	Adapter Plate	Yes, AP-LMS200200 Make: Holmarc	6750	Yes	100%
06	Base Plate	Yes, BP-LMS200200 Make: Holmarc	4510	Yes	100%
07	Right Angle Brackets	Yes, AB-LMS200200 Make: Holmarc	14431	Yes	100%
08	Servo Motorized Translation Stage Bundled with Controller and Power Supply	Yes, Model: MTS-6565-1-01, MRS-100, HO-SPLF-04, Make: Holmarc	319826	Yes	100%
09	Glass Plates	Base Diameter 70 mm, Cone angle 30 to 55 degrees, Height 50 mm. Base Diameter 100 mm, Cone angle 30 to 55 degrees, Height 75 mm. (Male-Female), Base Diameter 100 mm Hemi-spherical surface, Local Make	53100	Yes	50%
Total (Rs Twenty Three Lakhs Forty Eight Thousand Nine Hundred Eighty Nine only)			2348989	--	--

Image of Equipment:

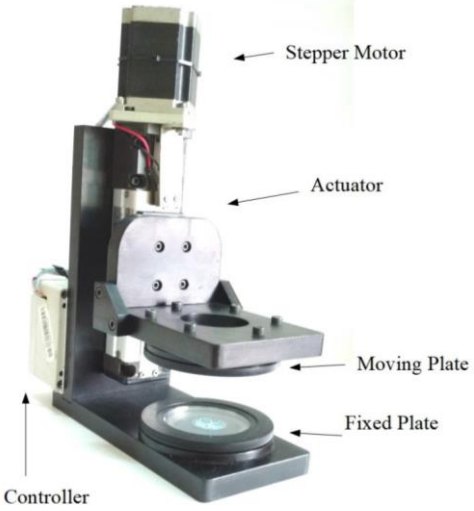


Figure 7: Lifting plate Hele-Shaw Cell apparatus (Preliminary stage).

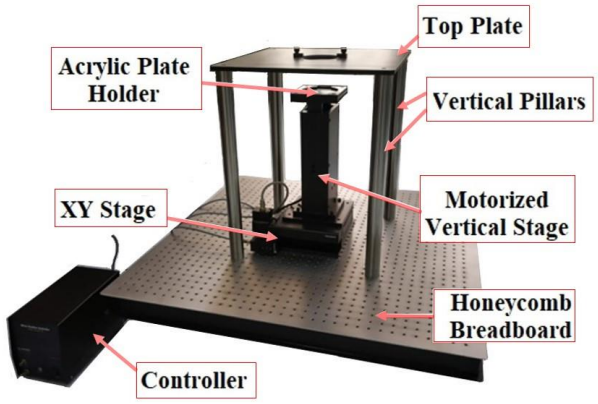


Figure 8: Assembly of lifting plate Hele-shaw cell for the fractal formation on curved surfaces.

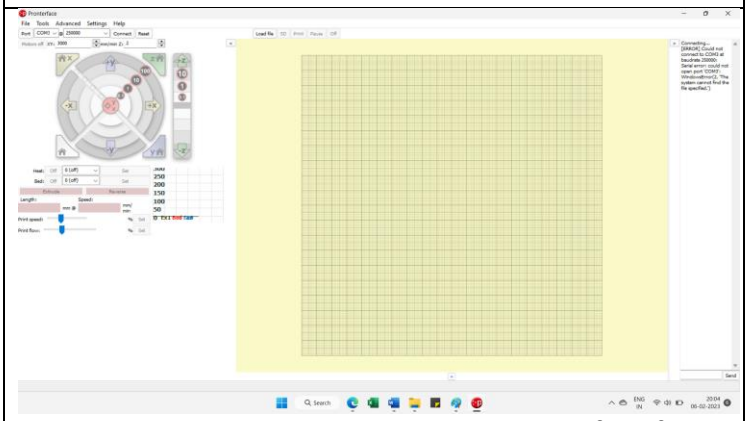


Figure 9: Developed Graphical User Interface for controlling Experimental Setup.

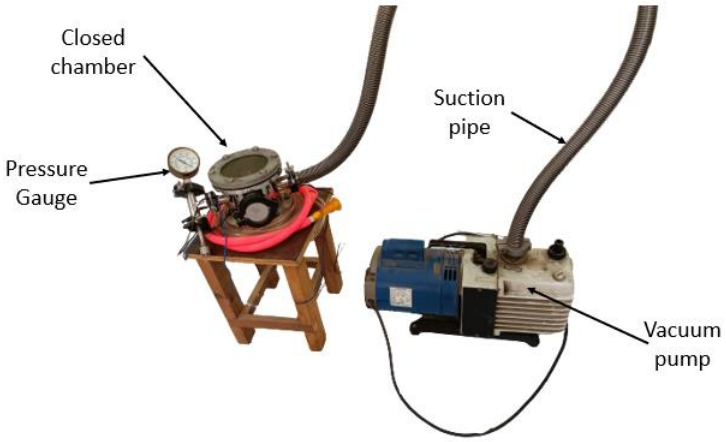


Figure 10: Degassing Unit for removing air bubbles from PDMS mold solution.

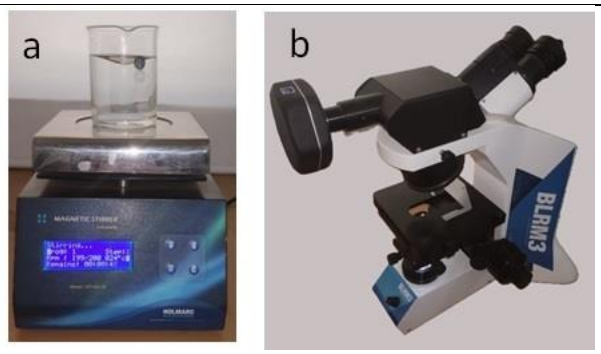


Figure 11: (a) Magnetic stirrer and (b) microscope

Figure 12: Multi Syringe Pump set up for purging fluids in micro-channels.

Figure 13: Certificate of ASME best paper award in IDETC 2022 Conference in Micro- and Nanosystems track at St. Louis, USA.