PROGRESS REPORT (Year 2022-23)

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:** 05th March 2023 Capital (Non Recurring) – Rs. 2295889/- General (Recurring) – Rs. 205646/-

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 experimentation limitations of initial prototype developed to study viscous fingering through lifting plate Hele-shaw cell setup (Figure 1) were identified. Based on the previous developed prototype and design presented in the project proposal the new experimental setup is executed (refer Figure 7). New experimental apparatus was designed in CAD software. Various equipment's, accessories and custom made parts required for the new experimental setup are ordered and assembled together (refer Figure 7). The modularity, easy to reconfigured and upgrade are the key aspects in the system design. The data acquisition system employed to capture the viscous fingering process is NI system and indigenously developed GUI (refer Figure 8).

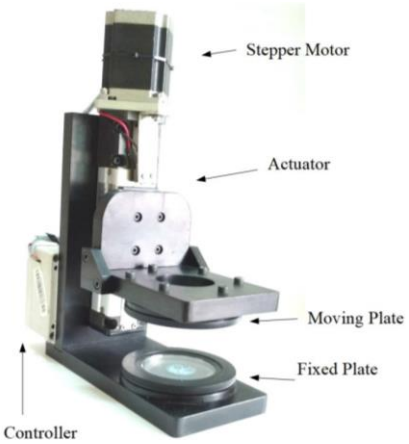


Figure 1: Lifting plate Hele-shaw Cell apparatus

The newly developed system is ready to conduct experiment for various configuration of Hele-Shaw cell. The developed system is able to investigate viscous fingering study on various flat plates (circular and polygonal surfaces) and curved surfaces. Experiments are conducted on developed system to investigate the viscous fingering on polygonal surfaces which are not yet explored.

Effect of various polygonal surface plates and especially its corners on fractal formation in the lifting plate Hele-shaw cell apparatus is investigated and validated on ANSYS Fluent software platform.

Different polygonal (geometrical) shaped surface plates fabricated from acrylic have been utilized in the experiments. Appropriate process parameters are selected and fractals are formed on these plates in lifting plate Hele-Shaw cell apparatus. Fractals formed on triangular plate are shown in Figure 2.

(a) Fabricated triangular acrylic plate (b) Fractals formed on triangular plate

Figure 2: Fractals formed on triangular plate

Effect of process parameters in lifting plate Hele-Shaw cell - gap between the two plates and plate lifting velocity on fractal formation is studied, where role of capillary number (Ca) and normalised dimension

(b/D) ratio of plates are of major consideration. Micro-fractal development is seen influenced by the ratios of Ca and b/D. Experiments were conducted for particular combinations of these two, and the results are plotted graphically as shown in Figure 3.

Similar experiments conducted using pentagonal plates and micro-fractals were formed.

Fractal formation with the process parameters in these experimentation trials were also simulated on ANSYS software platform. Simulation results were in good agreement with the results of experimentation in the lab. Net-shaped fractal pattern is formed by introducing anisotropies in the form of source-holes.

Microchannels on flat plates were made from net-shaped fractal patterns through PDMS mould formation (Figure 4). These microchannel arrangements were tested for micro mixing of fluids (coloured dye). PDMS mould was bonded to borosilicate glass plate by oxygen plasma treatment (refer Figures 4 and 9). With the syringes, coloured dye were inlet at the peripheral fractals of mould. Fluids mixed at micro-level could be retrieved from the centre (refer Figures 5 and 10).

Further investigation is also in process for development of 3D net shaped structures on lateral curved surfaces. 3D conical plates were fabricated from acrylic material and used on the setup for fractal formation. Semi-cone angle of conical surface is varied between the range 55° to 30°. Fractals formed on conical surfaces with 55° semi-cone angle is shown in Figure 6.

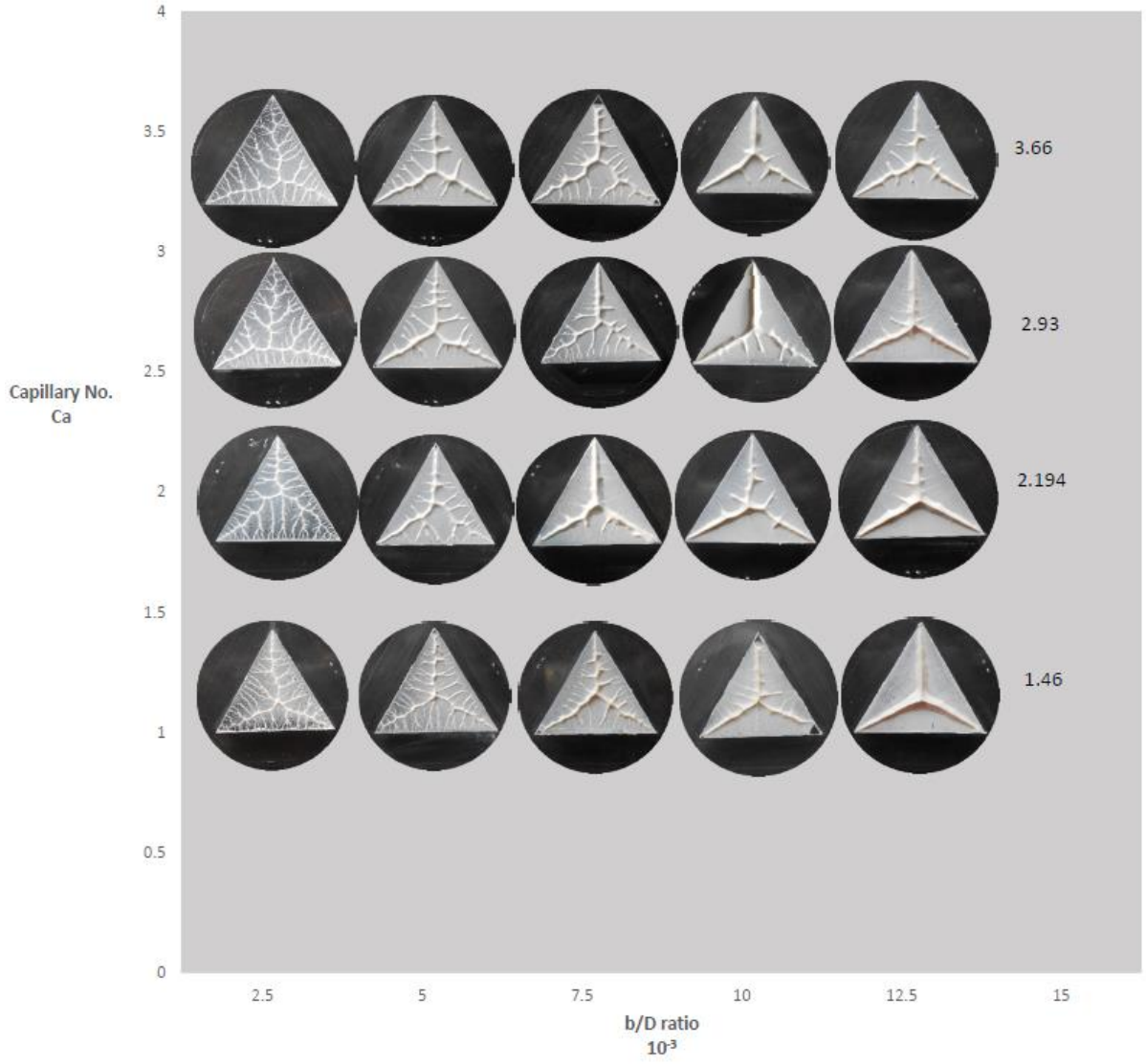


Figure 3: Micro-fractals formed for different combinations of Ca & b/D ratio on triangular plate

Figure 4: PDMS mould formed

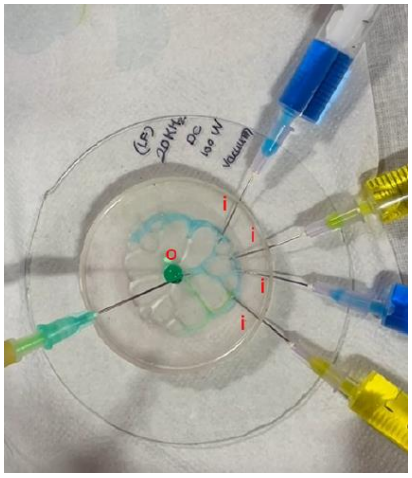
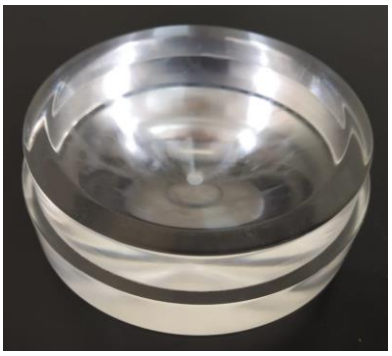


Figure 5: Micro mixing arrangement



(a) Fabricated lower conical plate

(b) Fabricated upper conical plate

(c) Fractals formed on lower conical plate

(d) Fractals formed on upper conical plate

Figure 6: 3D net shaped structures formed on conical surfaces.

7.2 New Observations:

Fractal-like structures are formed when highly viscous fluid is squeezed to specific thickness between two parallel plates and upper plate is lifted with controlled velocity. Low viscosity fluid penetrates high viscosity fluid through the path with minimum restriction and the fractal-like structure is formed. Dimensional characteristics of fractals depend upon capillary number (Ca) and normalized dimension (b/D) ratio of plate. Higher fractal creation is associated with lower b/D ratio values, and vice versa.

Fractals form less frequently at higher values of Ca and dimensionless gap. The development of fractals rises as the Ca values rise. In contrast, b/D ratio has a significant influence on fractals.
Introducing source-holes anisotropies on flat plates lead to ordered net-shaped fractal pattern. Dimensions of net-shaped pattern depends upon the diameter of source-hole and its location on the plate. Fractals that are generated from the source-holes which are closer to the centre propagate faster than the one from the farther source-holes and shield with the adjacent.
When fractals are formed on conical plates, dimensional characteristics of fractals depend upon semi-cone angles of plate in addition to thickness of high viscosity fluid between the two mating surfaces and plate lifting velocity.

7.3 Innovations:

- Development of fractal-like net-shaped micro-structures by a novel lithography-less method that takes place spontaneously.
- Simple designed and developed experimental setup can be used for the development of net-shaped micro-structures on plane (flat) as well as curved surfaces.
- Micro-structures formed can be easily converted to micro-channels through PDMS mould formation that can be utilized in various micro-engineering applications, such as micro-mixing, micro heat exchangers etc.

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 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 11 for the ASME best paper award certificate)

Research work which remains to be done under project :

- Fractal like net-shaped patterns are to be formed on conical and hemi-spherical plates utilizing newly designed lifting plate Hele-Shaw Cell apparatus. Governing process parameters viz. gap between the upper and lower plate, plate lifting velocity, kinematic viscosity of high viscosity fluid are to be considered.
- Process plan for PDMS moulds for the 3D net-shaped patterns is to be articulated. Alternative resins for the mould formation will have to investigated.
- Moulds formed on flat surface plate are bonded with plane borosilicate glass plate substrate

by Oxygen Plasma treatment. In cone-shaped moulds, it is not feasible to use plane glass plates. Alternative substrate and bonding method is to be identified for cone-shaped PDMS moulds.

Ph.D Produced No: 03 (in progress)
Technical Personnel Trained = 04
Research Publications arising out of the present project: 03

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

(B) Papers published in Conference Proceedings, Popular Journals etc. – 03

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

Patents filed/ to be filed: To be filed

Major Equipment (Model and Make)

Sr. No	Sanctioned List	Procured (Yes/No) Model and Make	Cost (Rs. In lakhs)	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	Purchase Order Placed: Base Diameter 50 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), Local Make	--	--	--
Total			22,95,889	--	--

Image of Equipment:

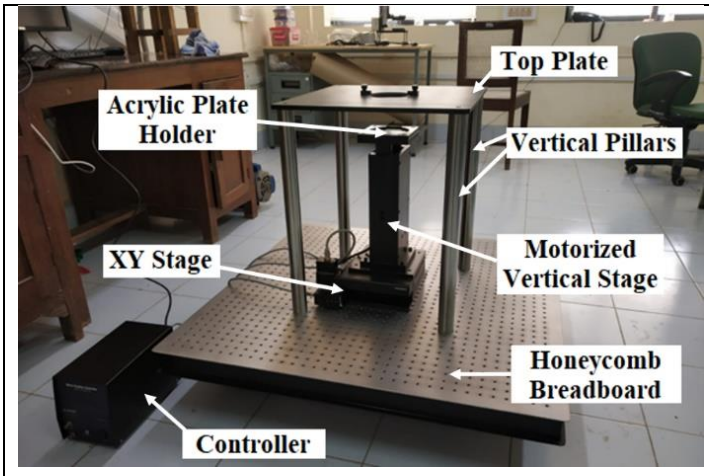


Figure 7: Assembly of Experimental setup for study of Fractals on Curved Surfaces.

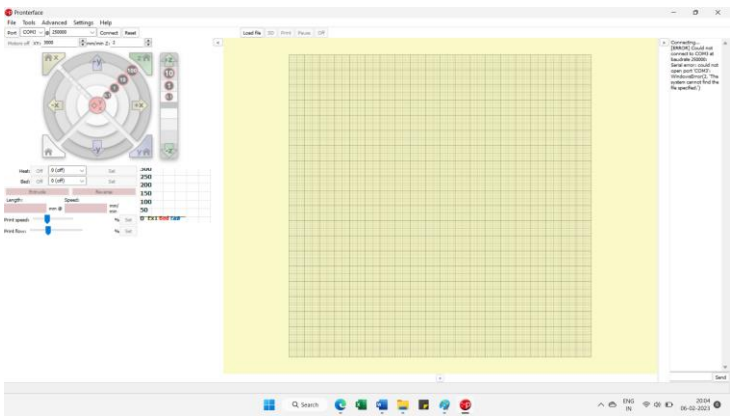


Figure 8: Developed Graphical User Interface for controlling Experimental Setup.

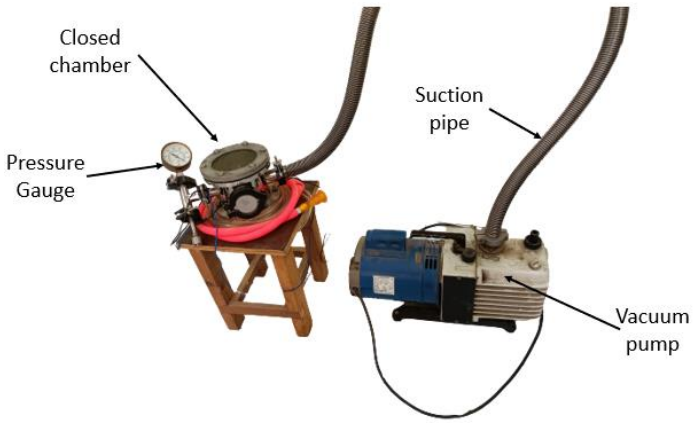


Figure 9: Degassing Unit for removing air bubbles from PDMS mould solution.

Figure 10: Multi Syringe Pump set up for purging fluids in micro-channels.

Figure 11: Certificate of ASME best paper award in IDETC 2022 Conference in Micro- and Nanosystems track at St. Louis, USA.