1.3.3 Number of the student studied course on experimental learning through Project Work / Internship

Programme Name: M.Tech. Mechanical- Design Engineering Programme Code: 1-1408968333			
Year of offering: 2019-2020			
Sr. No.	**Name of the Course that include experiential learning through project work/field work/internship**	**Course code**	**Number of the student studied course on experiential learning through project work/field work/internship**
1.	Dissertation Phase I : Synopsis Submission Seminar	Dissertation	08
2.	Dissertation Phase II : Progress Seminar	Dissertation	06
3.	Dissertation Phase III : Progress Report presentation and submission		
4.	Dissertation Phase IV : Final presentation and submission of report		
5.	Dissertation Viva voce		

PRINCIPAL,
College of Engineering
PANDHARPUR

पुण्यश्लोक अहिल्यादेवी होळकर सोलापूर विद्यापीठ, सोलापूर
Punyashlok Ahilyadevi Holkar Solapur University, Solapur
केगाव, सोलापूर - ४१३ २५५, महाराष्ट्र (भारत)
दुरध्वनी : ०२१७-२७४४७७१/७२/७३/ (११ लाईन्स), फॅक्स : ०२१७-२३५१३०
संकेतस्थळ: http://su.digitaluniversity.ac/www.sus.ac.in ई-मेल: bcudpgbutr@sus.ac.in

पुण्यश्लोक अहिल्यादेवी होळकर सोलापूर विद्यापीठ
NAAC Accredited-2015
'B' Grade (CGPA 2.62)

Ph.D Research Section विस्तारीत क्रमांक - १२३ , १२४, १२५

Ref No. PAHSUS/ARD/Ph.D.-I/2019/ 8148 **Date:** 23 OCT 2019

To,
The Principal,
SVERI's College of Engineering, Pandharpur,
Tal-Pandharpur, Dist-Solapur-413304.

Subject :- Approval of M.E./M.Tech. Mechanical Engineering Dissertation Title.
Reference :- RRC Meeting Dated 27/09/2019

Sir/Madam,

With reference to above Subject, I am directed to inform you that, Research & Recognition Committee has accorded approval to the title of **M.E./M.Tech. Mechanical Engineering** Dissertation, as mentioned overleaf.

You are requested to bring the approval to the notice of concerned guide and students.

Thanking you.

Yours Faithfully,

(Assistant Registrar)
Research Development (Ph.D.-I)

College of Engineering
Pandharpur,
Inward No. 897
Date - 06/11/2019

Copy to :-
The Director,
Board of Examinations and Evaluation,
P.A.H., Solapur University, Solapur.

To, HOD MECH / All concerned guides
Please inform all students & concerned guides
.../11/19

P.A.H. SOLAPUR UNIVERSITY, SOLAPUR

Statement showing who have applied for M.E. Dissertation in subject of : **Mechanical Engineering** **RRC date : 27/09/2019**

Name of Students and Address	Batch	Name of Guide and Address	Topic of Research work	Recommendations of RRC (with reason)
Mr. Jadhav Sanket Sanjayrao SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	ME Aug. 2013	**Prof. S. V. Jadhav** SVERI's College of Engineering, Pandharpur	"Comparison of Experimental and Numerical Analysis of Al-Sic Metal Matrix Composite	**Approved**
Miss. Jadhav Shubhangi Dilip SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	ME Aug. 2013	**Prof. S. V. Jadhav** SVERI's College of Engineering, Pandharpur	"Numerical and Experimental Analysis of Tuned Vibration Absorber to Find Optimum Position and Minimize Hand-Arm Vibration"	**Approved**
Mr. Sapkal Avinash Dattatray SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Dr. A. A. Utpat** SVERI's College of Engineering, Pandharpur	"An Experimental Analysis and Simulation of 3D PCM Technology"	**Approved**
Mr. Waghamare Dattatray A. SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Dr. N. D. Misal** SVERI's College of Engineering, Pandharpur	"Process Optimization of PCM on 3D Surface"	**Approved**
Mr. Vibhute Prakash Ashok SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Dr. B. P. Ronge** SVERI's College of Engineering, Pandharpur	"Design, Fabrication and Fluid Flow Analysis of Electromagnetically Actuated Check Valve Based Micropump."	**Approved**
Mr. Shinde Shekhar Gajanan SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Dr. R. R. Gidde** SVERI's College of Engineering, Pandharpur	"Study of Piezoelectric Actuation Based Valveless Micropump Used in Microfluidic Applications"	**Approved**
Mr. Gade Shubham Bapurao SVERI's College of Engineering, Tal- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Dr. B. P. Ronge** SVERI's College of Engineering, Pandharpur	"Optimization of Process Parameters for AISI H21 Material using Design of Experiment (DOE) Techniques"	**Approved**

Statement showing who have applied for M.E. Dissertation in subject of : **Mechanical Engineering** **RRC date : 27/09/2019**

Name of Students and Address	Batch	Name of Guide and Address	Topic of Research work	Recommendations of RRC (with reason)
·. Survase Ramling Suresh ERI's College of Engineering, l- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Prof. S. B. Bhosale** SVERI's College of Engineering, Pandharpur	"Manufacturing and Analysis of Natural Sisal Fiber and Sugar Cane Powder Hybrid Composite"	**Approved**
iss. Gaikwad Kanchan Sadashiv 'ERI's College of Engineering, l- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Dr. R. R. Gidde** SVERI's College of Engineering, Pandharpur	Design Optimization for Brake Pedal Used in Automobile Application"	**Approved**
r. Kamble Pravin Chandrakant 'ERI's College of Engineering, ıl- Pandharpur, Dist-Solapur-413304	M.Tech Aug.2018	**Prof. B. D. Gaikwad** SVERI's College of Engineering, Pandharpur	"Design and Development of Device for Measurement of Geometrical and Dimensional Tolerance of Gear of Planetary Gearbox."	**Approved**

(Asst. Registrar)
Research Depertment (Ph.D.-I)

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"An Experimental Analysis and Simulation of 3D PCM Technology"

has been submitted by

Mr. Avinash Dattatray Sapkal

for partial fulfillment Degree of Master of Technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to be the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

(Prof. Dr. A. A. Utpat)
Guide
Department of Mechanical Engineering

(Mr. P. A. Dhavale)
M.Tech Co-ordinator
Department of Mechanical Engineering

(Dr. S. S. Wangikar)
HOD
Department of Mechanical Engineering

B. Ronge
(Prof. Dr. B. P. Ronge)
Principal
SVERI's College of Engineering, Pandharpur

External Examiner (online)

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"Process Optimization of PCM on 3D Surface"

has been submitted by

Mr. Dattatray Anil Waghamare

for partial fulfillment Degree of Master of Technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to be the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

(Dr. N. D. Misal)
Guide
Department of Mechanical Engineering

(Prof. P. A. Dhavale)
M.Tech Co-ordinator
Department of Mechanical Engineering

(Dr. S. S. Wangikar)
HOD
Department of Mechanical Engineering

(Dr. B. P. Ronge)
Principal
SVERI's College of Engineering, Pandharpur

External Examiner (online)

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"Design, Fabrication and Fluid Flow Analysis of Electromagnetically Actuated Check Valve Based Micropump"

has been submitted by

Mr. Prakash Ashok Vibhute

for partial fulfillment Degree of Master of Technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to be the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

(Dr. B. P. Ronge)
Guide
Department of Mechanical Engineering

(Prof. P. A. Dhawale)
M.Tech Co-ordinator
Department of Mechanical Engineering

(Dr. R. R. Gidde)
Co-Guide
Department of Mechanical Engineering

(Dr. B. P. Ronge)
Principal
SVERI's College of Engineering, Pandharpur

(Dr. S. S. Wangikar)
HOD
Department of Mechanical Engineering

External Examiner (online)

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"Manufacturing and Analysis of Natural Sisal Fiber and Sugar Cane Powder Hybrid Composite"

has been submitted by

Mr. Ramling Suresh Survase

for partial fulfillment Master of technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to be the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

(Prof. S. B. Bhosale) Guide	**(Prof. P.A.Dhawale)** PG-Co-Ordinator	**(Dr. S. S. Wangikar)** Head, Dept. of Mech. Engg.

(Dr. B. P. Ronge)
Principal

(External Examiner)
Online

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"Study of Piezoelectric Actuation Based Valveless Micropump Used in Microfluidic Application"

has been submitted by

Mr. Shekhar Gajanan Shinde

for partial fulfillment Degree of Master of Technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to be the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

(Dr. R. R. Gidde)
Guide
Department of Mechanical Engineering

(Prof. P. A. Dhavale)
M.Tech Co-ordinator
Department of Mechanical Engineering

(Dr. S. S. Wangikar)
HOD
Department of Mechanical Engineering

(Dr. B. P. Ronge)
Principal
SVERI's College of Engineering, Pandharpur

External Examiner (online mode)

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"Optimization of Process Parameters for AISI H21 Material using Design of Experiment (DOE) Techniques"

has been submitted by

Mr. Shubham Bapurao Gade

for partial fulfillment Degree of Master of Technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to be the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

B. Ronge

(Dr. B. P. Ronge)
Guide
Department of Mechanical Engineering

(Dr. S. A. Sonawane)
Co-Guide
Department of Mechanical Engineering

(Dr. S. S. Wangikar)
HOD
Department of Mechanical Engineering

B. Ronge

(Dr. B. P. Ronge)
Principal
SVERI's College of Engineering, Pandharpur

(Prof. P. A. Dhavale)
M.Tech Co-ordinator
Department of Mechanical Engineering

External Examiner (online)

SOLAPUR UNIVERSITY

Solapur-Pune Highway, Kegaon, Solapur-413255, Maharashtra, INDIA.
Website : su.digitaluniversity.ac

सोलापूर विद्यापीठ
॥ विद्यया संपन्नता ॥

Sr. No.: 10/2017/A4 0799143

Statement of Grade for Faculty of Science & Technology-Master of Technology-Regular-Choice Based Credit System-Mechanical (Design Engineering)--Sem-IV
Examination: Mar-2020

Name: **SAPKAL AVINASH DATTATRAY (RATAN)**
PRN: **2018032500257377** Seat Number: **825737**
College: **College of Engineering, Gopalpur (COEP)**
Exam Center : 0

Paper Code	Paper Name			Credits	Grade Obtained	Grade Points	Earned Gr Points	Remark
7072301	Lab Practices			2.00	O	10.00	20.00	E,X
7072302	Dissertation Phase-I Synopsis Submission Seminar			2.00	O	10.00	20.00	E,X
7072303	Dissertation Phase-II Progress Seminar			8.00	O	10.00	80.00	E,X
7072307	Non Conventional Energy			3.00	A+	9.00	27.00	E,X
Sem-III	**Credit: 15.00**	**EGP: 147.00**	**SGPA: 9.80**	**Status: Pass**				
7072401	Dissertation Phase-III Progress Report Presentation & Submission			3.00	O	10.00	30.00	E,C
7072402	Dissertation Phase-IV Final presentation & Submission of Report			6.00	O	10.00	60.00	E,C
7072403	Dissertation Viva-Voce			6.00	O	10.00	60.00	E,C
Sem-IV	**Credit: 15.00**	**EGP: 150.00**	**SGPA: 10.00**	**Status: Pass**				
Sem-III (Seat No: 825737 Exam Event: Oct-2019)								
	Total Credit: 15.00	**EGP: 147.00**	**SGPA: 9.80**	**Status: Pass**				
M.Tech.-I (Seat No: 825737 Exam Event: Oct-2019)								
	Total Credit: 45.00	**EGP: 354.00**	**SGPA: 7.87**	**Status: Pass**				
Cumulative	**Total Credits : 75.00**	**Total EGP : 651.00**	**SGPA : 8.68**		**CGPA : 8.68**		**Status : Pass**	
	Grand Total : 1614/2200	**Equivalent Percentage : 73.36 %**		**Grade : A+ (Very Good)**		**Ordinance : Not Applied**		

Abbreviations: Gr: Grade, SGPA: Semester Grade Point Average, CGPA: Cumulative Grade Point Average, EGP: Earned Grade Points, E: Exempted, C: Current Appearance, X: Past Performance, N: Not Exempted, UM: Unfair Means, FC: Fail in University Assessment, FR: Fail in College Assessment

Punyashlok Ahilyadevi Holkar Solapur University ★ Board of Examinations and Evaluation

Statement No: 5953928
Date: 29 Dec 2020

Director
Board of Examinations and Evaluation

SOLAPUR UNIVERSITY

Solapur-Pune Highway, Kegaon, Solapur-413255. Maharashtra, INDIA.
Website : su.digitaluniversity.ac

सोलापूर विद्यापीठ
॥ विद्यया संपन्नता ॥

Sr. No.: 10/2017/A4 0799140

Statement of Grade for Faculty of Science & Technology-Master of Technology-Regular-Choice Based Credit System-Mechanical (Design Engineering)--Sem-IV
Examination: Mar-2020

Name: **WAGHAMARE DATTATRAY ANIL (GIRIJA)**

PRN: **2018032500257346** Seat Number: **825734**

College: **College of Engineering, Gopalpur (COEP)**

Exam Center : ()

Paper Code	Paper Name			Credits	Grade Obtained	Grade Points	Earned Gr Points	Remark
7072301	Lab Practices			2.00	O	10.00	20.00	E,X
7072302	Dissertation Phase-I Synopsis Submission Seminar			2.00	O	10.00	20.00	E,X
7072303	Dissertation Phase-II Progress Seminar			8.00	O	10.00	80.00	E,X
7072307	Non Conventional Energy			3.00	A	8.00	24.00	E,X
Sem-III	**Credit: 15.00**	**EGP: 144.00**	**SGPA: 9.60**	**Status: Pass**				
7072401	Dissertation Phase-III Progress Report Presentation & Submission			3.00	O	10.00	30.00	E,C
7072402	Dissertation Phase-IV Final presentation & Submission of Report			6.00	O	10.00	60.00	E,C
7072403	Dissertation Viva-Voce			6.00	O	10.00	60.00	E,C
Sem-IV	**Credit: 15.00**	**EGP: 150.00**	**SGPA: 10.00**	**Status: Pass**				
Sem-III (Seat No: 825734 Exam Event: Oct-2019)								
	Total Credit: 15.00	**EGP: 144.00**	**SGPA: 9.60**	**Status: Pass**				
M.Tech.-I (Seat No: *961802 Exam Event: Oct-2019)								
	Total Credit: 45.00	**EGP: 388.00**	**SGPA: 8.62**	**Status: Pass**				
Cumulative	**Total Credits : 75.00**	**Total EGP : 682.00**	**SGPA : 9.09**		**CGPA : 9.09**		**Status : Pass**	
	Grand Total : 1693/2200	**Equivalent Percentage : 76.95 %**		**Grade : A+ (Very Good)**	**Ordinance : Not Applied**			

Abbreviations: Gr: Grade, SGPA: Semester Grade Point Average, CGPA: Cumulative Grade Point Average, EGP: Earned Grade Points, E: Exempted, C: Current Appearance, X: Past Performance, N: Not Exempted, UM: Unfair Means, FC: Fail in University Assessment, FR: Fail in College Assessment

Punyashlok Ahilyadevi Holkar Solapur University
Board of Examinations and Evaluation

Statement No: 5953925

Date: 29 Dec 2020

Director
Board of Examinations and Evaluation

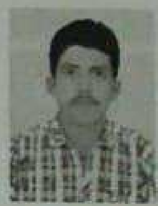
SOLAPUR UNIVERSITY

Solapur-Pune Highway, Kegaon, Solapur-413255, Maharashtra, INDIA.
Website : su.digitaluniversity.ac

सोलापूर विद्यापीठ

Sr. No.: 10/2017/A4 0799141

Statement of Grade for Faculty of Science & Technology-Master of Technology-Regular-Choice Based Credit System-Mechanical (Design Engineering)--Sem-IV
Examination: Mar-2020



Name: **VIBHUTE PRAKASH ASHOK (SANGITA)**
PRN: **2018032500257354** Seat Number: **825735**
College: **College of Engineering, Gopalpur (COEP)**
Exam Center : ()

Paper Code	Paper Name			Credits	Grade Obtained	Grade Points	Earned Gr Points	Remark
7072301	Lab Practices			2.00	O	10.00	20.00	E,X
7072302	Dissertation Phase-I Synopsis Submission Seminar			2.00	O	10.00	20.00	E,X
7072303	Dissertation Phase-II Progress Seminar			8.00	O	10.00	80.00	E,X
7072307	Non Conventional Energy			3.00	A	8.00	24.00	E,X
Sem-III	**Credit: 15.00**	**EGP: 144.00**	**SGPA: 9.60**	**Status: Pass**				
7072401	Dissertation Phase-III Progress Report Presentation & Submission			3.00	O	10.00	30.00	E,C
7072402	Dissertation Phase-IV Final presentation & Submission of Report			6.00	O	10.00	60.00	E,C
7072403	Dissertation Viva-Voce			6.00	O	10.00	60.00	E,C
Sem-IV	**Credit: 15.00**	**EGP: 150.00**	**SGPA: 10.00**	**Status: Pass**				
Sem-III (Seat No: 825735 Exam Event: Oct-2019)								
	Total Credit: 15.00	**EGP: 144.00**	**SGPA: 9.60**	**Status: Pass**				
M.Tech.-I (Seat No: 825735 Exam Event: Oct-2019)								
	Total Credit: 45.00	**EGP: 360.00**	**SGPA: 8.00**	**Status: Pass**				
Cumulative	**Total Credits : 75.00**	**Total EGP : 654.00**	**SGPA : 8.72**		**CGPA : 8.72**		**Status : Pass**	
	Grand Total : 1664/2200	**Equivalent Percentage : 75.64 %**		**Grade : A+ (Very Good)**		**Ordinance : Not Applied**		

Abbreviations: Gr: Grade, SGPA: Semester Grade Point Average, CGPA: Cumulative Grade Point Average, EGP: Earned Grade Points, E: Exempted, C: Current Appearance, X: Past Performance, N: Not Exempted, UM: Unfair Means, FC: Fail in University Assessment, FR: Fail in College Assessment

Punyashlok Ahilyadevi Holkar Solapur University ★ Board of Examinations and Evaluation

Statement No: 5953926
Date: 29 Dec 2020

Director
Board of Examinations and Evaluation

SOLAPUR UNIVERSITY

Solapur-Pune Highway, Kegaon, Solapur-413255. Maharashtra, INDIA.
Website : su.digitaluniversity.ac

सोलापूर विद्यापीठ
॥ विद्यया संपन्नता ॥

Sr. No.: 10/2017/A4 0799142

Statement of Grade for Faculty of Science & Technology) Master of Technology-Regular-Choice Based Credit System-Mechanical (Design Engineering)--Sem-IV
Examination: Mar-2020

Name: **SHINDE SHEKHAR GAJANAN (SUSHAMA)**

PRN: **2018032500257362** Seat Number: **825736**

College: **College of Engineering, Gopalpur (COEP)**

Exam Center : **()**

Paper Code	Paper Name			Credits	Grade Obtained	Grade Points	Earned Gr Points	Remark
7072301	Lab Practices			2.00	O	10.00	20.00	E,X
7072302	Dissertation Phase-I Synopsis Submission Seminar			2.00	O	10.00	20.00	E,X
7072303	Dissertation Phase-II Progress Seminar			8.00	O	10.00	80.00	E,X
7072307	Non Conventional Energy			3.00	A+	9.00	27.00	E,X
Sem-III	**Credit: 15.00**	**EGP: 147.00**	**SGPA: 9.80**	**Status: Pass**				
7072401	Dissertation Phase-III Progress Report Presentation & Submission			3.00	O	10.00	30.00	E,C
7072402	Dissertation Phase-IV Final presentation & Submission of Report			6.00	O	10.00	60.00	E,C
7072403	Dissertation Viva-Voce			6.00	O	10.00	60.00	E,C
Sem-IV	**Credit: 15.00**	**EGP: 150.00**	**SGPA: 10.00**	**Status: Pass**				
Sem-III (Seat No: 825736 Exam Event: Oct-2019)								
	Total Credit: 15.00	**EGP: 147.00**	**SGPA: 9.80**	**Status: Pass**				
M.Tech.-I (Seat No: *961806 Exam Event: Oct-2019)								
	Total Credit: 45.00	**EGP: 380.00**	**SGPA: 8.44**	**Status: Pass**				
Cumulative	**Total Credits : 75.00**	**Total EGP : 677.00**	**SGPA : 9.03**	**CGPA : 9.03**		**Status : Pass**		
	Grand Total : 1734/2200	**Equivalent Percentage : 78.82 %**		**Grade : A+ (Very Good)**	**Ordinance : Not Applied**			

Abbreviations: Gr: Grade, SGPA: Semester Grade Point Average, CGPA: Cumulative Grade Point Average, EGP: Earned Grade Points, E: Exempted, C: Current Appearance, X: Past Performance, N: Not Exempted, UM: Unfair Means, FC: Fail in University Assessment, FR: Fail in College Assessment

Punyashlok Ahilyadevi Holkar Solapur University ★ Board of Examinations and Evaluation

Statement No: 5953927

Date: 29 Dec 2020

Director
Board of Examinations and Evaluation

SOLAPUR UNIVERSITY

Solapur-Pune Highway, Kegaon, Solapur-413255, Maharashtra, INDIA.
Website : su.digitaluniversity.ac

सोलापूर विद्यापीठ
॥ विद्यया संपन्नता ॥

Sr. No.: 10/2017/A4 0799138

Statement of Grade for Faculty of Science & Technology-Master of Technology-Regular-Choice Based Credit System-Mechanical (Design Engineering)--Sem-IV
Examination: Mar-2020

Name: **GADE SHUBHAM BAPURAO (SANGITA)**
PRN: **2018032500257296** Seat Number: **825729**
College: **College of Engineering, Gopalpur (COEP)**
Exam Center : 0

Paper Code	Paper Name	Credits	Grade Obtained	Grade Points	Earned Gr Points	Remark
7072301	Lab Practices	2.00	O	10.00	20.00	E,X
7072302	Dissertation Phase-I Synopsis Submission Seminar	2.00	O	10.00	20.00	E,X
7072303	Dissertation Phase-II Progress Seminar	8.00	O	10.00	80.00	E,X
7072307	Non Conventional Energy	3.00	A+	9.00	27.00	E,X
Sem-III	**Credit: 15.00** **EGP: 147.00** **SGPA: 9.80**	**Status: Pass**				
7072401	Dissertation Phase-III Progress Report Presentation & Submission	3.00	O	10.00	30.00	E,C
7072402	Dissertation Phase-IV Final presentation & Submission of Report	6.00	O	10.00	60.00	E,C
7072403	Dissertation Viva-Voce	6.00	O	10.00	60.00	E,C
Sem-IV	**Credit: 15.00** **EGP: 150.00** **SGPA: 10.00**	**Status: Pass**				
Sem-III (Seat No: 825729 Exam Event: Oct-2019)						
	Total Credit: 15.00 **EGP: 147.00** **SGPA: 9.80**	**Status: Pass**				
M.Tech.-I (Seat No: 961807 Exam Event: Mar-2019)						
	Total Credit: 45.00 **EGP: 400.00** **SGPA: 8.89**	**Status: Pass**				
Cumulative	**Total Credits : 75.00** **Total EGP : 697.00** **SGPA : 9.29**	**CGPA : 9.29**		**Status : Pass**		
	Grand Total : 1774/2200 **Equivalent Percentage : 80.64 %**	**Grade : A+ (Very Good)**		**Ordinance : Not Applied**		

Abbreviations: Gr: Grade, SGPA: Semester Grade Point Average, CGPA: Cumulative Grade Point Average, EGP: Earned Grade Points, E: Exempted, C: Current Appearance, X: Past Performance, N: Not Exempted, UM: Unfair Means, FC: Fail in University Assessment, FR: Fail in College Assessment

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SVERI's
College of Engineering, Pandharpur

Department of Mechanical Engineering

M.Tech. Project Sample Report

A.Y.: 2019-2020

A

DISSERTATION

ON

"Study of Piezoelectric Actuation Based Valveless Micropump Used in Microfluidic Application"

Submitted to

Punyashlok Ahilyadevi Holkar Solapur University, Solapur

Submitted by

Mr. Shekhar Gajanan Shinde

In the partial fulfillment for the award of

M. Tech (Design Engineering)

Under the Faculty of Engineering and Technology

Under the Guidance of

Dr. Ranjitsinha R. Gidde

Department of Mechanical Engineering

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

A.Y. 2019-2020

SVERI

SVERI's COLLEGE OF ENGINEERING, PANDHARPUR

CERTIFICATE

This is to certify that the dissertation entitled

"Study of Piezoelectric Actuation Based Valveless Micropump Used in Microfluidic Application"

has been submitted by

Mr. Shekhar Gajanan Shinde

for partial fulfillment Degree of Master of Technology in Mechanical (Design Engineering) as per curriculum laid by the Punyashlok Ahilyadevi Holkar Solapur University, Solapur during the academic year 2019-2020. He has carried out the dissertation work under my guidance and to the best of our knowledge the work reported here is does not form the part of any other thesis or dissertation.

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DECLARATION

I hereby declare that the dissertation entitled **"Study of Piezoelectric Actuation Based Valveless Micropump Used in Microfluidic Application"** submitted to the PAH Solapur University, Solapur is a record of an original work done by me under the guidance of Dr. R. R. Gidde, Mechanical Engineering, SVERI's College of Engineering, Pandharpur and this work is submitted after thorough study and not copied. The results embodied in this thesis have not been submitted to any other University or Institutes.

Mr. Shekhar Gajanan Shinde

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ABSTRACT

The design and fabrication of piezoelectric actuation based valveless micropump has been carried out. The modelling of micropump is carried out using COMSOL Multiphysics 5.0. The performance of a piezoelectric actuation based valveless micropump in terms of flow rate has been investigated. A nozzle–diffuser based valveless micropump is modeled using a fluid–structure interaction and pzd approach. Further, the proposed piezoelectric actuation based micropump was fabricated using soft lithography technique and PCM and CO_2 laser engraving master moulds. The comparison between simulation and experimental results has been carried out validate the simulation results.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

The different abbreviations, acronyms and symbols, employed in the dissertation are introduced hereafter are as follows:

Abbreviation/ Acronyms	Description
μTAS	Micro Total Analysis System
PMMA	Poly-methyl-meth-acrylate
PDMS	Poly-di-methyl-siloxane
MEMS	Micro-Electro-Mechanical-System
FSI	Fluid Structure Interaction
EDM	Electric Discharge Machining
PCM	Photochemical Machining
3-D	Three-Dimensional
ρ	Density
PVM	Piezoelectric Valveless Micropump
E	Modulus of elasticity
ν	Poisson's ratio
E	Young's modulus (Pa)
G	Modulus of rigidity (Pa)
Q_{net}	Net flow rate (μl/min)
D_{PZT}	Diameter of PZT

Chapter 1
Introduction

Micropump is a pivotal component in microfluidic systems as it is essential for micro liquid handling and thus micropump has become an important research area. According to the definition of "MEMS", miniaturized pumping devices fabricated by micromachining technologies are called micropump. A micropump is a device which can be used to generate controlled flow rate in the range of L/min to ml/min. During recent years several different micropumps have been reported based on different principles and actuation mechanisms including electro-osmotic, electromagnetic, piezoelectric, electrostatic, shape memory alloy.

Among various actuation possibilities, piezoelectric (PZT) actuation offers advantages in terms of high deflection, PZT actuated valveless micropumps have advantages of simple structure and improved reliability due to elimination of valves. The structure comprises a pair of nozzle-diffuser elements and a fluid chamber. In the supply mode, the diaphragm deflects upward which results in a negative pressure inside the fluid chamber due to which fluid is drawn into the chamber via the inlet (diffuser)and outlet (nozzle). As the pressure drop across a nozzle is higher compared to that across a diffuser, more fluid is drawn via the inlet compared to that via the outlet. In the pump mode, the diaphragm moves downward thus creating a positive pressure and more fluid leaves via the outlet (diffuser) compared to that via the inlet (nozzle). Thus, a net flow from the inlet to the outlet is achieved. As piezoelectrically actuated valve less micropumps (PAVM) have simple structure and no internal movable parts, there is less risk of clogging the valves when it pumps fluid containing particles.

Micromachined pumps are essential in micro liquid handling systems. Different micropumps have been developed during the years with different advantages and drawbacks. A valve-less pump which uses the flow directing effect of diffuser elements having piezoelectric actuation is presented. One of the main advantages of the pump is the absence of moving parts, except the pump diaphragms, which reduces the risk of mechanical failure. All tested pumps show good performance and one of the micromachined versions is very good compared with most of the other micropumps.

1.1 Overview of Micropump

1.1.1 Basic Structure of Micropump

A piezoelectric micropump is similar to diaphragm type mechanical micropumps but do not use check valves to rectify flow. Instead nozzle/diffuser elements are used as flow rectifiers. A schematic illustration of valveless micropump is shown in Fig. 1.1

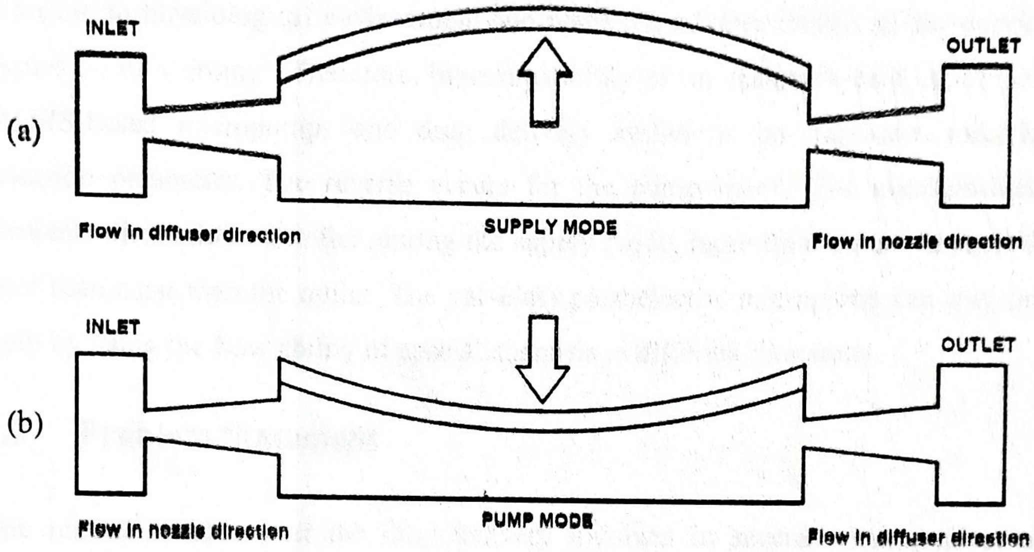


Fig. 1.1. Schematic of basic structure of valveless micropump (a) supply mode and (b) pump mode [2].

The operation of the micropump is based on the deflection of the diaphragm. As observed, during the supply mode, the diaphragm deflects upward and thus creating a negative pressure inside the chamber. In this situation, the fluid flows into the chamber through both the inlet and outlet.

Micropumps for drug delivery applications must meet basic requirements, which are listed as follows:

1. **Drug biocompatibility**
2. **Actuation safety**
3. **Desired and controllable flow rate**
4. **Small chip size**
5. **Less power consumption**

Biocompatibility of MEMS-based micropumps is becoming increasingly important and is regarded as a key requirement for drug delivery systems. Biocompatibility is defined as the ability of a material to perform with an appropriate host response in a specific application. As micropumps in drug delivery systems can be implanted inside the human body, therefore the materials used for fabrication must be able to fulfil rigorous biocompatibility and biostability requirements . The implanted micropump based drug delivery system must be able to withstand long term exposure to physiological environment and resist the adverse impact of surrounding tissues on its working . Therefore, biocompatibility of the materials used to fabricate MEMS-based micropumps and drug delivery system is an important materials selection parameter. The reverse occurs for the pump mode. The nozzle/diffuser elements direct flow such that during the supply mode, more fluid enters through the inlet than exist than the outlet. The valveless piezoelectric micropump can transport fluid by using the flow ability of special channels in different directions.

1.2 Problem Statement

The precise control over the drug delivery involved in several vital applications including healthcare is required for achieving a therapeutic effect. For such precise control/manipulation of the drugs, micropumps are used. These micropumps are basically of two types viz. check valve-based and valveless micropumps. The valveless micropumps are preferable due to the congestion-free operation of diffuser/nozzle valves. In this paper, design optimization of a valveless. This dissertation focuses on the investigation of piezoelectric actuation based valveless micropump, fabrication and demonstration of prototype.

1.3 Objectives

- To study different types of micropumps used in micro-fluidic applications.
- To carry out simulation of piezoelectric actuation-based valve less micropump.
- To fabricate piezoelectric actuation-based micropump.
- To perform comparison between simulation and experimental results.

1.4 Methodology

The methodology employed to achieve the objectives is as follows:

- **To study different types of micropumps used in micro-fluidics application:**

  The micropump is one of main components of drug delivery system that provides the actuation mechanism to deliver specific volumes of therapeutic agents/drugs from the reservoir. The requirements for drug delivery include a minimum flow rate in order of 10 μL/min or more, small size and high reliability. The various types of micropumps and their actuation mechanisms will be studied. The detailed study of positive displacement (mechanical) and non-mechanical micropumps will carried.

- **To carry out simulation of a piezoelectric actuation based valveless micropump:**

  Simulation of piezoelectric actuation based micropump will be carried out using suitable software. The effect of various structural parameters and operating parameters on the functional characteristics of the piezoelectric micropump will be studied. The functional characteristics such as flow rate and back pressure will be considered to evaluate the performance of the micropump. In-depth analysis of pressure flow characteristics with respect to actuating voltage and frequency will be studied.

- **To carry out fabrication of a piezoelectric actuation based micropump:**

  After micropump design, whole structure of micropump will be fabricated using polymer-based materials viz. polymethacrylate (PMMA) and polydimethylsiloxane (PDMS). The micropump will be fabricated in three main layers namely bottom layer (functional layer), middle layer (diaphragm) and top layer (actuator layer). Bonding of three layers will be carried out using suitable method. The 3-dimensional piezoelectric actuator will be attached at the top of the diaphragm. The micropump supporting structure will be fabricated using acrylic.

- **To perform comparison between simulation and experimental results:**

  The simulation and experimental results will be compared on the basis of performance characteristics. The performance characteristics such as flow rate and back pressure of a valveless micropump can be enhanced through proper selection of geometrical and operating parameters. The performance characteristics such as flow rate and back pressure of a valveless micropump are mostly influenced by geometrical as well as operating parameters. The results of flow rate and back pressure will be compared. The estimated error between two results will be studied.

Chapter 2
Literature Review

Development of all PDMS (substrate and the membrane material) valveless PZT micropumps have been reported in the literature. Many researchers have done the improvement in micropumps consist of a chamber and different diffuser design which is oscillated periodically by an actuation mechanism for different kinds of applications. Some of their work is summarized below.

Micropumps and microvalves build the foundation of many different microfluidic systems. Microvalves control routing, timing, and separation of fluids within a microfluidic device and are crucial for designs with complex functionality whereas micropumps are used for controlling and modulating fluid flow in microfluidic devices. Microvalves are used to rectify fluidic flow and used in pairs for directing fluid flow in or out of a micropump or individually in a microchannel. These microvalves can be either static or dynamic. Static microvalves are mostly mechanical check valves having micro- machined orifice and a polymer-based deflectable sealing element, whereas dynamic microvalves comprise nozzle/diffuser element, which functions as a valve. The studies on the micropump are grouped in two parts namely computational analysis, computational and experimental analysis. The literature is divided into three categories as follow:

2.1 Computational Approach

Gidde et al. [1] Micropumps are the most important components of lab-on-a-chip devices, which are becoming popular recently due to their enormous advantages. Among the different designs of micropumps, the nozzle–diffuser valveless design is the most preferred one due to simplicity in manufacturing. For the simulation of these pumps, the local fluid structure interaction modeling is important to get the performance accuracy.

Gidde et al. [2] The precise control over the drug delivery involved in several vital applications including healthcare is required for achieving a therapeutic effect. For such precise control/manipulation of the drugs, micropumps are used. These micropumps are basically of two types viz. check valve-based and valveless micropumps. The valveless micropumps are preferable due to the congestion-free operation of diffuser/nozzle valves. An optimal set of design parameters for the proposed micropump is identified.

Gidde et al. [3] A valveless micropump based on an electromagnetic actuation for drug delivery application has been designed. The parametric studies are performed to examine the effect of divergence angle, neck width, diffuser length, height and diameter of the pump chamber and diaphragm thickness on the flow rate.

T. Barkat et al. [4] The behavior of a valveless, diaphragm-founded, piezoelectric micropump is studied and simulated. The nature of the piezoelectric actuator is a PZT-5H piezo-disk and the diaphragm is made of Silicon dioxide (SiO2). Applying Fluid-Structure Interaction (FSI) approach, the simulation for the valveless micropump is carried out in COMSOL 3.5 Multiphysics.

Nayana et al. [5] presented design and simulation of some discrete parts of a valveless piezoelectric micropump for drug delivery system. They have simulated core components of the micropump individually, which include actuator (required for creating a pumping effect) and diffuser/nozzle elements (required to rectify forward direction) by using COMSOL Multiphysics.

Cui et al. [6] designed a valveless micropump excited by a piezoelectric actuator for medical applications. To investigate the behaviors of the micropump, a complete electric–fluid–solid coupling model was built upon using ANSYS software. They analyzed the effects of the geometrical dimensions on the micropump characteristics and its efficiency. To enhance the performance of the micropump, some important diffuser parameters, such as the diffuser length, the diffuser angle, and the neck width should be optimized.

X He et al. [7] Based on the Coanda effect, a novel valveless micropump is presented in this paper, the special bluff-body is utilized to enhance the Coanda effect and increase the net flow of the micropump. In order to reveal the influence of structural parameters on the performance of novel micropump, five samples with different chamber radii (5 mm and 9 mm) are fabricated by silicon-based MEMS technology.

2.2 Experimental Approach

Pandey et al. [8] The three-dimensional numerical simulation of a micropump, including diffuser and analytical modeling of the micropump flow rate. The numerical simulation of the diffuser is performed in all possible flow regimes to optimize its geometry for maximum efficiency. The core component of the system is a piezoelectric diaphragm that can convert the reciprocating movement of a diaphragm actuated by a piezoelectric actuator into a pumping effect. The deflection in the diaphragm was analyzed by applying the voltages and pressures over different size of membrane. Nozzle/diffuser elements were used to direct the flow from inlet to outlet.

Dereshgi et al. [9] This micropump studies two piezoelectric based micropumps for biomedical applications. First, Single Diaphragm Micropump (SDM) was proposed as reference micropump. Second, Bi-diaphragm Micropump (BDM) was designed to increase the net flow rate. Essentially, the novelty of this work was that the BDM had two vibrational diaphragms that were placed in parallel. The sinusoidal voltage was applied with 180-degrees phase shift to BDM's piezoelectric actuators.

Zhang et. al. [10] In order to prevent the backward flow of piezoelectric pumps, a single active chamber piezoelectric membrane pump with multiple passive check valves. Under the condition of a fixed total number of passive check valves, by means of changing the inlet valves and outlet valves' configuration, the pumping characteristics in terms of flow rate and backpressure are experimentally investigated.

S. Revathi et. al. [11] A micropump, including diffuser and analytical modelling of the micropump flow rate. The numerical simulation of the diffuser is performed in all possible flow regimes to optimize its geometry for maximum efficiency. The deflection of the piezoelectric polymer composite circular actuator is analytically solved by theory of bending plates to determine the volumetric change and flow rate.

Sateesh J. et al. [12] Controlled drug delivery in medical application plays a prominent role, that can be achieved by micro-drug delivery devices. The efficient working of the controlled drug delivery system depends on the micropump in it. This paper presents theoretical, design and simulated analysis of piezoelectrically actuated micropump constructed using PZT-5H material, quartz channel, and a PDMS membrane. The designed micro pump is analyzed for different structural, material changes by considering turbulent and laminar flows.

2.3 Computational and Experimental Approaches

Shen et al. [13] characterized a reciprocating PMMA ball-valve micropump actuated with a miniaturized cylindrical electromagnetic circuit, which was fabricated in PMMA and PDMS. They have optimized the structure of the electromagnet that actuates a rare-earth permanent magnet embedded in a PDMS pumping membrane by finite element calculations. Powder blasting and conventional micromachining techniques were used for fabricating micropump. The micropump exhibits a backpressure up to 35 kPa.

Das et al. [14] The flow behaviour and performance parameters of a diffuser-nozzle element of a valveless micropump have been investigated for different geometric and flow properties. When a fluctuating pressure is imposed on the inlet boundary of a diffuser-nozzle element, there is a net flow in diffuser direction due to the dynamic effect.

Zhou et al. [15] studied a single-chamber planar valveless micropump, driven by an external electromagnetic actuator by employing both the finite element method (FEM) and experimental analysis to characterize the pump performance at variable working conditions. The micropump features a pair of micro diffuser and nozzle elements, which rectify the fluid flow.

Yamahata et al. [16] presented the microfabrication and characterization of a ball valve micropump in the glass, which is magnetically actuated using the sinusoidal current of an external electromagnet. They used a polymer membrane with the permanent magnet embedded which gives rise to a large actuation stroke, which makes the micropump bubble-tolerant and self-priming.

Aggarwal et al. [17] studied piezoelectrically actuated pyramidal valveless micropumps through experimentally analysis. Valveless micropumps based on silicon and glass substrate are fabricated using MEMS technology. The reported micropumps have low footprint, high flowrate and backpressure. Thus, these micropumps are especially suited for biological applications as these can withstand adequate amount of backpressure.

Wangikar et al. [18] The purpose of work is to study the parametric effect and optimization for Photochemical machining (PCM) of copper. The PCM has been carried out on copper by using ferric chloride as an etchant. The photo tool has been selected based on the analysis for better overall quality and minimum edge deviation. The experiments have been performed varying the (control parameters) concentration of etchant, temperature and the etching time.

S. Revathi et. al. [28] Valveless micropumps are extensively used in micro fluidic systems, including health care monitoring and diagnostic devices, computer devices, and so on, as it forms the critical component in the microsystem for precise and controlled fluid handling. This work proposes the design and development of a novel, significantly low cost, planar micropump with piezoelectric polymer composite, consisting of lead zirconate titanate for actuation.

A shape memory alloy (SMA) actuator and a polydimethylsiloxane (PDMS) elastic tube were used to realize a simple pump. A liquid plug in a flow channel could be moved forward and backward reversibly by exploiting the shape memory properties of the actuator. Two SMA sheets were used to create a peristaltic pump capable of moving a solution forward and backward over a long distance.

2.4 Research Gap

From the above literature survey, it is evident that simulation and experimental based analysis of piezo-electric actuation based valveless micropumps have been addressed previously by researchers. Although, considerable work on piezoelectric actuation based valveless micropump, investigations based on fully coupled electro-fluid–structural (pzt and fsi physics interface) interactions is not performed till date due to the complexities in respect of coupling two physics. Further, fabrication on the basis of low-cost criteria has not been done till date. Hence there is scope to perform numerical analysis and low-cost based fabrication of the piezoelectric micropump.

Chapter 3

Fundamental Aspects of Micropump

In the past decade, there has been a growing interest for the development of microfluidic systems for various applications like biological and chemical analysis, lab on chip diagnostics and drug delivery. Micropumps are an essential component in building the total fluid control system. In such system, it is essential for micro liquid handling, and thus micropump has become a vital research area. A micropump is a device which can be used to generate accurate flow rate in the range of μl/min to ml/min in accordance with the application. Presently several different micropumps have been described based on different principles and actuation mechanisms, which includes electro-osmotic, electromagnetic, piezoelectric, electrostatic, shape memory alloy etc. Compared with other actuation mechanisms, the piezoelectric actuation can provide a good reliability and moderate pressure at low power consumption, which is preferred for medical applications.

3.1 Characteristics of Microfluidics

Microfluidic systems have proved highly successful in biomedical applications by minimizing the size of electrophoresis chips, drug delivery systems, microfluidic mixers, pumps and valves, devices for cell or protein patterning, and microfluidic switches. Specially a PDMS pump is a device that is optimized for rapid prototyping and has proven to be a good material for microfluidic pump devices. First, one must know what PDMS means, PDMS stands for Polydimethylsiloxane and is most widely used as a silicon-based organic polymer. It is known for its unusual flow characteristics. The material is usually clear, inert, non-toxic, and non-flammable.

The benefits of such microfluidic devices are smaller sizes, better performance, reduction in power consumption, lowers costs, disposability, integration of control electronics, and the new functionality and reaction possibilities. These types of microfluidic devices have several characteristics and have flow that is generally laminar. They deal with smaller volumes of fluid, which results in higher precision of mixing and is safer to use with toxic and hazardous chemicals. Also these devices have high surface to volume ratio that results in effective heating and cooling.

3.2 Classification of Micropumps

According to the definition of "MEMS", miniaturized pumping devices fabricated by micromachining technologies are called micropumps. In general, micropumps can be classified as either mechanical or non-mechanical micropumps. The micropumps that have moving mechanical parts such as pumping diaphragm and check valves are referred to as mechanical micropumps where as those involving no mechanical moving parts are referred to as non-mechanical micropumps. Mechanical type micropump needs a physical actuator or mechanism to perform pumping function. The most popular mechanical micropumps discussed here include electrostatic, piezoelectric, shape memory alloy (SMA), bimetallic, ionic conductive polymer film (ICPF), electromagnetic and phase change type.

Non-mechanical type of micropump has to transform certain available non-mechanical energy into kinetic momentum so that the fluid in microchannels can be driven. Non-mechanical micropumps include magnetohydrodynamic (MHD), electro-hydrodynamic (EHD), electroosmotic, electrowetting, bubble type, flexural planar wave (FPW), electrochemical and evaporation based micropump. The classification of micropumps is shown in Fig. 3.1 MEMS technology has been successfully applied in biomedical field with the recent growth of implantable drug delivery systems. Silicon as substrate material has been used extensively as a good biocompatible material, however a trend towards the use of polymers as substrate material is growing as polymer materials are widely used in medicine and are suitable for human implantation. Polymer materials such as polymethylmethacrylate (PMMA), polydimethylsiloxane (PDMS), etc., possess relatively better biocompatibility and are increasingly being used in fabrication of MEMS micropumps. Micropumps have been investigated as drug delivery and disease diagnostic devices.

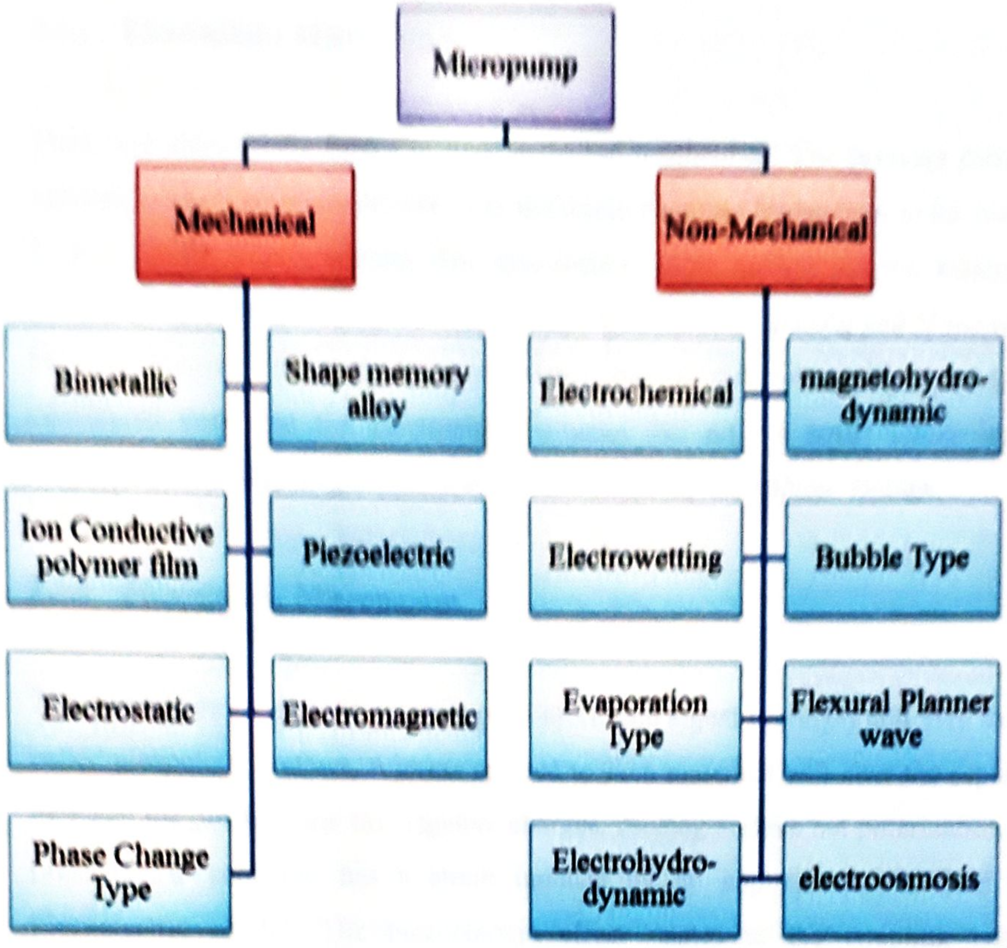


Fig. 3.1 Classification of Micropump

3.3 Mechanical Displacement Micropumps

These use the motion of a solid (such as a gear or diaphragm) or a fluid to generate the pressure difference needed to move fluid. The most common mechanical displacement micropumps are diaphragm pumps. Their actuation mechanisms are varied. They need a physical actuator for the pumping and they have moving parts. The actuator has to run itself with dead volume in the chamber. Fluid flow is achieved by oscillatory or rotational pressure forces. The oscillations create pressure), which is a function of the stroke volume inside the chamber and produced by the actuator. Examples of mechanical micropumps include piezoelectric, electrostatic, thermo pneumatic, electromagnetic, bimetallic, Ion Conductive Polymer Films (ICPF)and Shape Memory Alloy (SMA).

3.3.1 Electrostatic Micropumps

These use electrostatic forces in their actuation mechanism. The pressure difference induced by the membrane deflection in the pump chamber forces fluid in the reservoir to flow in the microchannels. The electrostatic force applied on the electrostatic plates. a the surface area of the electrodes, X the electrode spacing and V the applied voltage. Fabrication of these mechanisms on an electronic chip is generally considered easy, but the electrostatic actuator has only a small stroke and the deflection of the diaphragm can be easily controlled by the applied voltage.

3.3.2 Piezoelectric Micropumps

The conversion of mechanical energy to electronic signal (voltage) and vice versa is called piezoelectric effect. A stress applied to such materials will alter the separation between the positive and the negative charges, causing surface net polarization. This piezoelectric actuation has a strain induced by an applied electric field on a piezoelectric crystal. The piezoelectric effect relates to the coupling between mechanical deformation and electrical polarization. Piezoelectric mechanism finds common use in the reciprocating micropumps of drug delivery and other biomedical applications. Main advantages of piezoelectric actuators include large actuation force, fast response and simple structure. Their fabrication, however, is complex as is processing of piezoelectric materials. Another disadvantage is the comparatively high actuation voltage and small stroke.

3.3.3 Thermo-pneumatic Micropumps

In these types of micropumps, a chamber full of air is periodically and alternately expanded and compressed by a pair of heaters and cooler. The periodic change in the volume of the chamber gives the membrane a regular momentum so fluid can flow out. This type generates relatively large induced pressure and membrane displacement. Two disadvantages are the need for the driving power to be maintained at a constant and specific level and the slow response. The thermo-pneumatic actuation has a thermally induced volume change and/or phase change of fluids sealed in a cavity with at least one compliant wall. The pressure increase in liquids is expressed as:

$$\Delta P = E\left[\beta \Delta T - \frac{\Delta V}{V}\right] \tag{3.1}$$

With ΔP being the pressure change, E the bulk modulus of elasticity, β the thermal expansion coefficient, ΔT is the temperature increase and $\frac{\Delta V}{V}$ is the volume change percentage.

3.3.4 Shape Memory Alloy Micropumps (SMA)

SMAs are metals that show two unique properties such as pseudo elasticity and Shape Memory (SM). The diaphragm of SMA micropumps is made mostly of Titanium/Nickel alloy (TiNi), which is a highly suitable material for micropump actuators because of its high recoverable strain and actuation force capability for large pumping rates and high operating pressures. Its high work output per unit volume makes it suitable in sizes for MEMS applications. They can change shape when subjected to a stimulus. The SM effect involves a phase transformation between two solid phases: the austenite phase (at high temperatures) and the marten-site phase (at low temperatures). When heated to austenite start temperature, the material starts forming a single-variant austenite. If not subjected to mechanical constraint, the material will return to a pre-deformed shape, retained upon cooling back to marten-site phase. If subjected to mechanical constraint, the material will exert a large force while assuming a preformed shape. Main advantages of micro SMA pumps are high force-to-volume ratio, ability to recover large transformation stress and strain upon heating and cooling processes, high damping capacity, and biocompatibility. Their disadvantages are the need for specific SMA materials, relatively high power consumption and uncontrollable deformation of the SMA owing to temperature sensitivity.

3.3.5 Bimetallic Micropumps

Bimetallic actuation functions differently on different Coefficients of Thermal Expansion (CTE) of materials. The diaphragm of bimetallic micropump is made of two different metals having different CTEs. Bonding mechanism of dissimilar materials and their subjection to temperature changes induce thermal stresses because the coefficients of the metals differ, providing a means for actuation. The implementation extremely simple with large forces generated but the deflection of a diaphragm is only can be achieved by thermal alternation. The key advantage is that bimetallic micropumps require relatively low voltages than the other types of micropumps. Their main disadvantage is their unsuitability to high-frequency operation.

3.3.6 Ion-Conductive Polymer Film Micropumps (ICPF)

ICPFs are polymer MEMS actuators that can be actuated in aqueous environments with large deflection. They need lower input power than the conventional MEMS actuators. They are actuated by stress gradient from the ionic movement due to an electric field. Their key advantage is fast response. ICPF is composed of polyelectrolyte film with both sides chemically plated with platinum. The two films have high electrical conductivity. One diaphragm-end is fixed. An ICPF diaphragm can be controlled by bending it upside or downside in certain value of voltages applied to the electrodes within a certain duration.

The presence of an electric field causes the ions in both sides of the polymer molecule chain to move to the cathode. Simultaneously, each ion with a positive charge will take some water molecules and move towards the cathode. The ionic movement causes the cathode to expand and the anode to shrink. The presence of an alternating voltage signal will bend the films alternately. The applications of ICPF to delicate micro robots and micro manipulators that perform surgical operations have been reported. ICPF actuators have advantages such as low driving voltage, quick response and biocompatibility. They can work in aqueous environments. Their major drawback is low repeatability in batch fabrication.

3.3.7 Electromagnetic Micropumps

A typical magnetically actuated micropump has a chamber with inlet and outlet valves, a flexible membrane, a permanent magnet and a set of drive coils. Either the magnet or the set of coils may be attached to the membrane. The strength of the magnet can be varied by changing the electric current flow through the coils. Current driven through the coils produces a magnetic field that creates attraction or repulsion between the coils and the permanent magnet which provides the actuation force. The electromagnetic actuation is realized by a solenoid plunger. The force developed by the actuator depends on the applied current and on the number of turns. A miniaturized electromagnetic actuator comprises a soft magnetic mass suspended by a spring beam and an external solenoid coil. Their main features are high power consumption and heat dissipation. Their disadvantage is the difficulty in miniaturization, owing to the size of the required solenoid coil.

3.4 Principle of Piezoelectric Valveless Micropump (PVM)

The basic principle behind the operation of this pump is the differences between pressure losses in the inlet and outlet ports, both are of the nozzle/diffuser kind. The way this port behaves depends of the flow direction on each instant, so each port behaves as a nozzle when the flow is entering in the larger area and like a diffuser when the flow is entering the smaller area. Under laminar flow regime the pressure drop is bigger for a nozzle that for a diffuser, assuming a similar geometry. Taking this into account it is clear that when the membrane moves upward the fluid is absorbed on both ends, but the pressure drop on the outlet is bigger, because it is acting as a nozzle.

3.5 Micropump Design Parameters

At the design stage, several design parameters need to be considered to analyze the performance of the micropump.

The vital design parameters which are being considered are as follows:

- Maximum flow rate (Q_{max})
- Maximum back pressure (h_{max})
- Pump power (P_{pump})
- Pump efficiency (η_{pump}).

The maximum flow rate is obtained when the pump is working at zero back pressure. At the maximum back pressure, the flow rate of the pump becomes zero because back pressure opposes the work done by the pump. Pump head or net head, can be derived from the steady flow energy equation assuming incompressible flow and neglecting viscous work and heat transfer.

3.6 Piezoelectric Effect

A piezoelectric material is capable of converting electrical energy into mechanical energy and vice versa. The direct piezoelectric effect states that these materials, when subjected to mechanical stress, generate a proportional electric charge. Gas lighters, and some acceleration and pressure sensors make use of the direct piezoelectric effect. The inverse piezoelectric effect indicates that the same material when subjected to and electrical field, become proportionally strained. Buzzers and force sensors use the inverse piezoelectric effect.

If the piezoelectric material is exposed to an electric field (voltage) it consequently lengthens or shortens proportional to the voltage. E.g. Crystal Oscillators, crystal Speakers, record player Pic ups, actuators etc. The materials with positive piezoelectric effect must have inverse piezoelectric effect, and the piezoelectric coefficients of the same material in the positive and inverse piezoelectric effects are same. The higher the piezoelectric coefficient is, the higher energy conversion efficiency of piezoelectric materials.

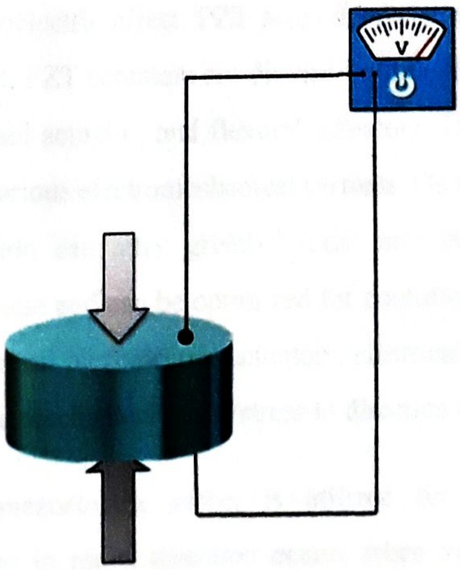


Fig. 3.2 If the applied voltage has the opposite polarity then the material contracts.

$$x = d\,E \text{ (strain = d × electric field)}$$

An applied electric field E produces a proportional strain x (linear effect), expansion or contraction, depending on polarity. Effects of PZT shown in Fig. 3.2 and 3.3.

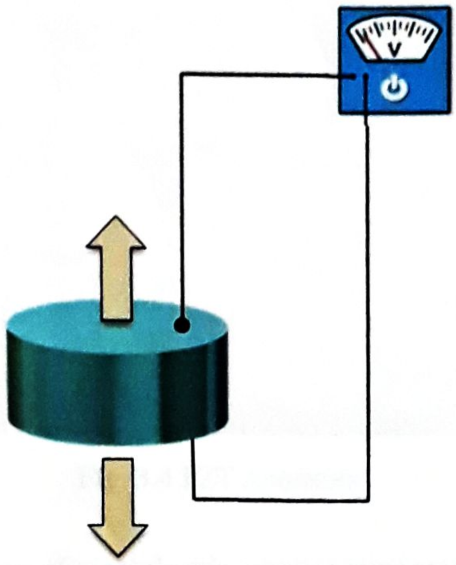


Fig. 3.3 If the applied voltage has the same polarity then the material expands

3.7 Piezoelectric Actuators

Piezoelectric materials generate electrical charge when stress is applied known as direct piezoelectric effect and mechanical strain when an electrical field is applied known as converse piezoelectric effect. PZT actuators convert electrical voltage into mechanical displacement. PZT actuators are divided in three basic categories namely, axial actuators, transversal actuator, and flexural actuators. These actuators are used as vital components in various electromechanical systems. On the basis of application, the actuator configuration can vary greatly. Axial and transversal piezoelectric actuators have high stiffness and can be optimized for controlled movements and high forces. In case of transversal piezoelectric actuators, electrical field/charge is applied in thickness direction and mechanical strain/stress in direction of plane is produced.

This converse piezoelectric effect is utilized for actuating micropump diaphragm. Displacement in radial direction occurs when voltage is applied to an actuator. When this displacement is blocked, a blocking force (a measure of the stiffness of actuator) is developed. As a result of this blocking force, diaphragm gets deflected in upward and downward direction during suction and pump mode of the micropump.

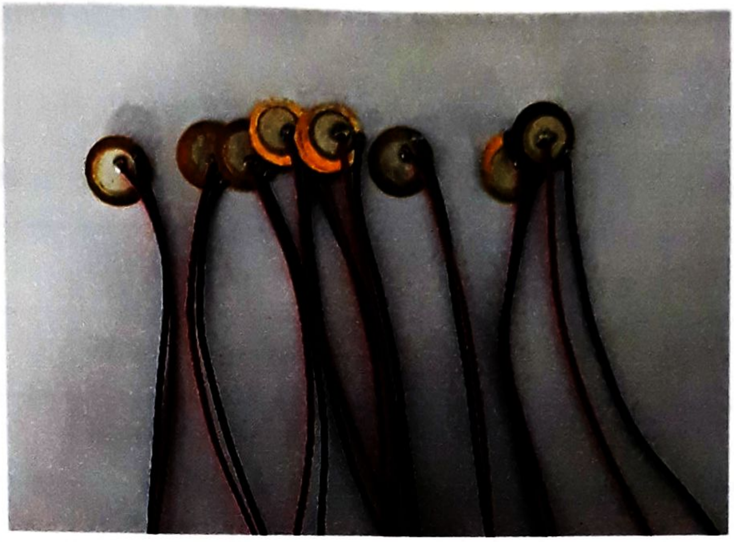
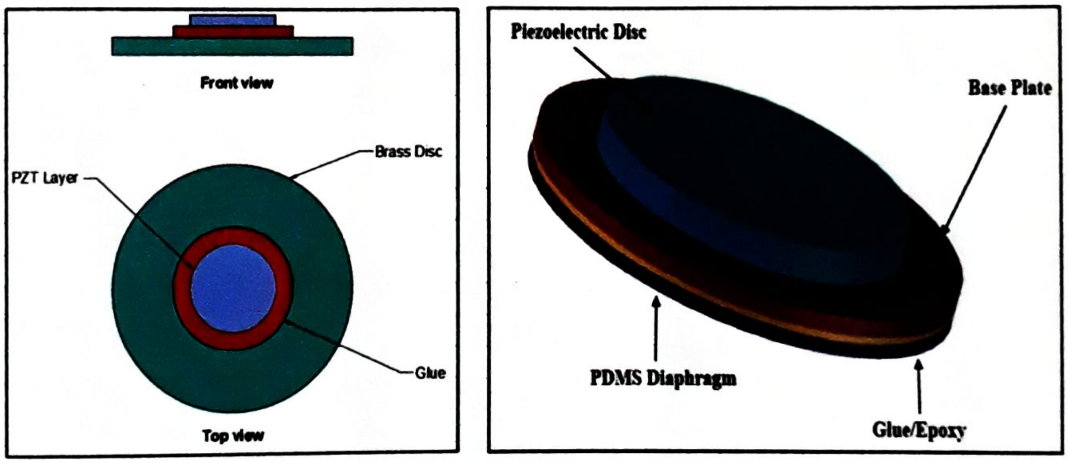


Fig. 3.4 PZT Actuators

Fig. 3.4 shows a schematic of piezoelectric actuator composed of a PZT layer, a brass substrate, glue/epoxy layer and a PDMS diaphragm.



(a) (b)

Fig. 3.5. Schematics of the Piezoelectric disc (a) 2-D View and (b) 3-D View

Piezoelectric actuation is the most commonly utilized actuation method for micropump technology. Fig. 3.5 shows the 2D and 3D view of piezoelectric disc which include different layer of PZT. This method was the first to be tested due to its attractive characteristics. This type of material provides a comparatively high stroke volume, a high actuation force, and a quick mechanical response. Also, on a fabrication level piezoelectric material, such as PZT, is commercially available for quick integration into the particular fabricated device. Hence, piezoelectric actuator as per the details shown in the Table 3.1 has been used for the study [20].

Table 3.1 Dimension of piezoelectric actuator

Sr. No.	Parameter	Values	Unit
1.	PZT layer diameter	7.5	mm
2.	PZT layer thickness	200	µm
3.	Brass disc external diameter	12	mm
4.	Brass disc thickness	140	µm

Chapter 4
Simulation of the PZT Micropump

The numerical modelling of the piezoelectric valveless micropump is described in this chapter. COMSOL Multiphysics 5.0 was used to model the piezoelectric valveless micropump which is capable of performing fluid flow analysis using piezoelectric (pzt) and fluid–structure interaction (fsi) Multiphysics interface modules.

4.1 Model Geometry

The schematics of a piezoelectric actuation based valveless micropump is presented in Fig. 4.1 The depth of the pump chamber and the nozzle-diffuser elements is H. A piezoelectric actuator comprises different elements namely a brass disc of thickness t_{br} as supporting layer and piezo element of thickness t_{pzt} and diameter d_{pzt} which is glued to the diaphragm using epoxy glue layer of thickness t_e.

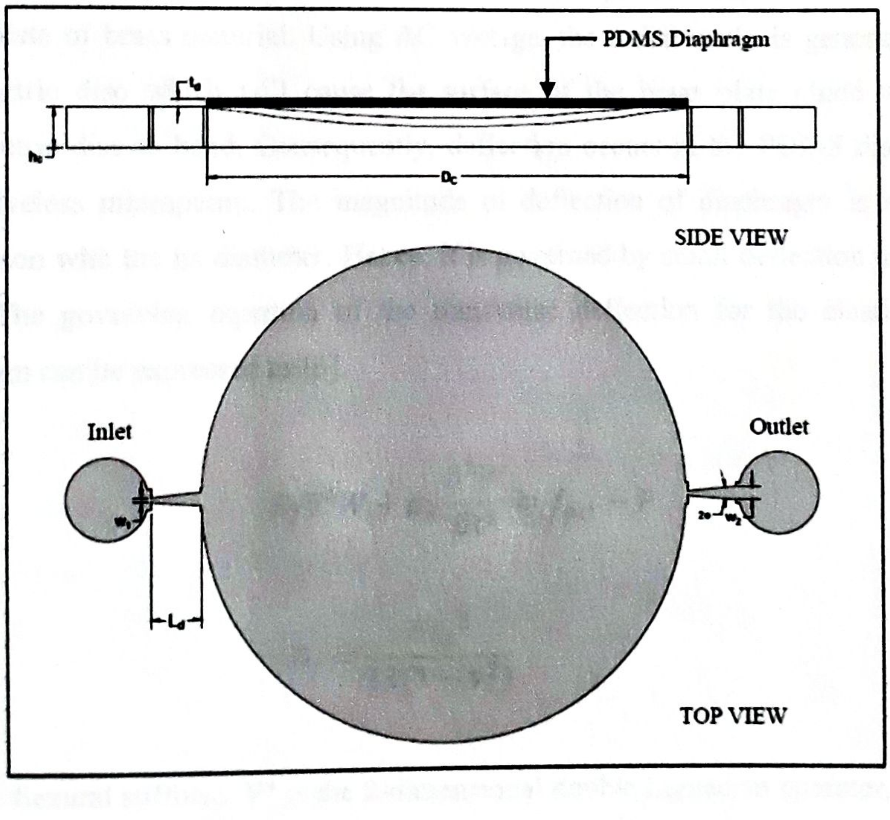


Fig. 4.1 Schematic of Piezoelectric Valveless Micropump

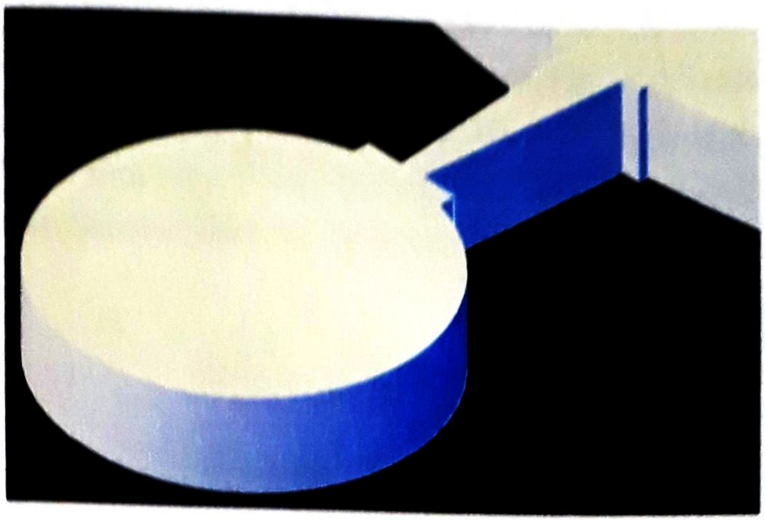


Fig. 4.2. Micropump model showing diffuser at the Inlet

4.2 Governing Equation

The two physics interface modules namely, piezoelectric devices (pzt) for the electro-structural parts and fluid–structure interaction (fsi) for fluid and structure domains, respectively were used to model the whole piezoelectric actuation based valveless micropump. The piezoelectric actuator consists of the piezoelectric disc and the thin elastic plate of brass material. Using AC voltage, the radial strain is generated in a piezoelectric disc which will cause the surface of the brass plate glued with the piezoelectric disc to bend. Consequently, deflection occurs in the PDMS diaphragm of a valveless micropump. The magnitude of deflection of diaphragm is small in comparison with the its diameter. Hence, it is governed by small deflection theory of plates. The governing equation of the transverse deflection for the elastic pump diaphragm can be expressed as [6].

$$D_f \nabla^4 W + \rho_d \frac{\partial^2 W}{\partial t^2} = f_{act} - P \qquad (4.1)$$

$$D_f = \frac{E t_d{}^3}{12(1 - \nu^2)} \qquad (4.2)$$

D_f is the flexural stiffness, ∇^4 is the 2-dimensional double Laplacian operator, E is the Elastic modulus, m is the Poisons ratio of the diaphragm material, t_d is the thickness of the diaphragm, and ρ_d is the density of the diaphragm material. fact is the periodic actuating force due to the strain of the actuator, and P is the dynamic pressure exerted on the diaphragm by the liquid. In this case, the pump diaphragm is assumed to be clamped to the brass plate. The flow is considered as an incompressible laminar flow, which can be described using the mass continuity Eq. [26].

$$\rho_f \frac{D\vec{V}}{Dt} = \rho_f \vec{g} + \mu \nabla^2 \vec{V} - \nabla P \qquad (4.3)$$

$$\frac{\partial \rho_f}{\partial t} + (\vec{V}.\nabla)\partial \rho_f = 0 \qquad (4.4)$$

where, ρ_f is the density of the liquid; $\vec{V}$ is the velocity vector; μ is the viscosity of the liquid.

4.3 Boundary Conditions

The fixed and zero displacement boundary conditions were applied at the edges of the diaphragm. To ensure zero relative motion at the interface between the diaphragm, layer of epoxy glue, brass disc and PZT element the 'always bonded boundary condition' has been employed. The PZT element is actuated using a sinusoidal voltage.

$$V(t) = V_0 \sin(2\pi f_{act} t) \qquad (4.5)$$

The pressure boundary condition is employed at both inlet and outlet, and a no-slip boundary condition is applied at the walls. The working fluid used for the simulation is assumed to be incompressible, and the flow of fluid within the micropump is assumed as laminar one.

Table 4.1 Material properties and geometrical dimensions.

Element	Parameters	alues
Diffuser	Neck or throat width, w_1 (mm)	0.1
	Outlet width, w_2 (mm)	0.3
	Diffuser length (L_d)	1.1
	Divergence angle, 2θ (°)	10
	Depth, h_d (mm)	0.9
PDMS diaphragm	Diameter D_d (mm)	12.0
	Thickness, t_d (mm)	0.15
	Density, ρ_d (kg/m^3)	7800
	Young's modulus, E_d (kPa)	595
Pump chamber	Poisson's ratio, μ_d	0.49
	Diameter, D_c (mm)	12.0
	Height, h_c (mm)	0.9
Inlet/ Outlet	Inlet Diameter, d_i (mm)	2.0
	Outlet Diameter, d_o (mm)	2.0
	Inlet Depth, h_i (mm)	0.9

4.4 Simulations of the Piezoelectric Micropump

Three-dimensional simulations of the piezoelectric simulations are performed using pzd and fsi interface modules to determine the optimal set of dimensions and the operating conditions. The two domains namely, structural domain and fluid domain were coupled and meshed using grid system consisting of hexahedral elements. Simulations were run for few cycles to confirm about cycle-to-cycle variation in performance characteristics of the micropump.

The three-dimensional model of the piezoelectric micropump is shown in Fig. 4.2. Based on grid independency study, the grid as shown in Fig. 4.3 composed by structured meshing with hexahedral elements having maximum size and minimum size of 0.125 mm and 0.0125 mm, respectively was used to carry out simulations. Meshed model of valveless micropump as shown in Fig. 4.7.

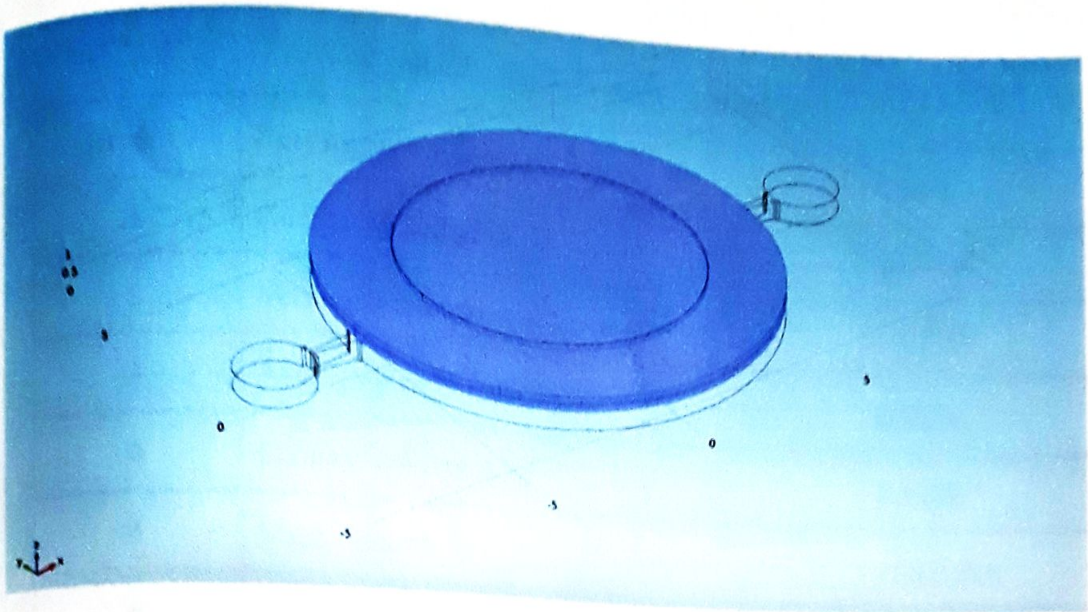


Fig. 4.3 Fluid domain (bottom layer) and structural domain

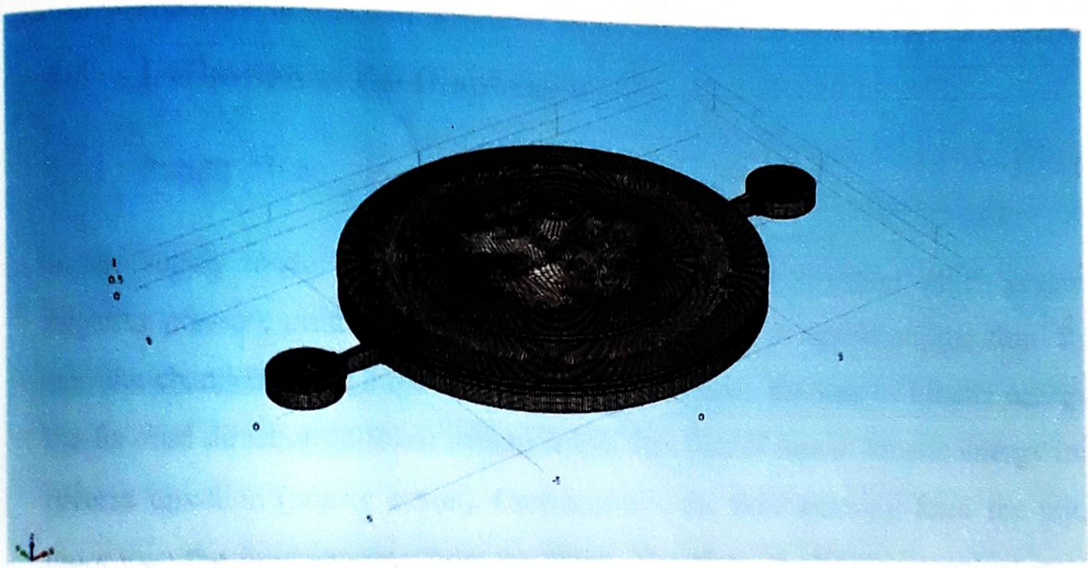


Fig. 4.4 Meshed model: Structural domain indicated by blue colored portion and fluid domain indicated by uncolored portion

Table 4.2 Parameters of complete mesh

Sr. No.	Element Type	Value
1.	Hexahedral element	285662
2.	Maximum element size	0.0801
3.	Minimum element size	0.00522

Table 4.3 Domain element statistics

Sr. No.	Parameter/variable	Value
1	Number of elements	285704
2	Minimum element quality	0.01789
3	Average element quality	0.9074
4	Element volume ratio	8.418E^{-4}
5	Mesh volume	108.9 mm^3
6	Maximum Growth rate	9.361
7	Average Growth Rate	1.085

4.5 Deflection of the Diaphragm

4.5.1 Supply Mode

In the supply mode, the diaphragm deflects in upward direction which creates a negative pressure inside the chamber. During this mode of operation, the fluid flows into the chamber through the inlet and outlet. However, the loss of kinetic energy in the forward direction (diffuser action) is less than that of loss of kinetic energy in the reverse direction (nozzle action). Consequently, the fluid entering from the inlet is more than the fluid entering from the outlet. Therefore, the fluid is supplied into the chamber from the inlet. During the supply mode, the diaphragm deflects in upward direction and fluid enters from both inlet and outlet through diffuser elements. It can be observed that the fluid entering through diffuser/nozzle element at the inlet during the supply mode is more than that of the flow exiting during the pump mode as a result of flow rectification caused as a result of difference in the pressure drop across nozzle and diffuser elements. Fig. 4.5 shows the Deflection of the diaphragm during supply mode.

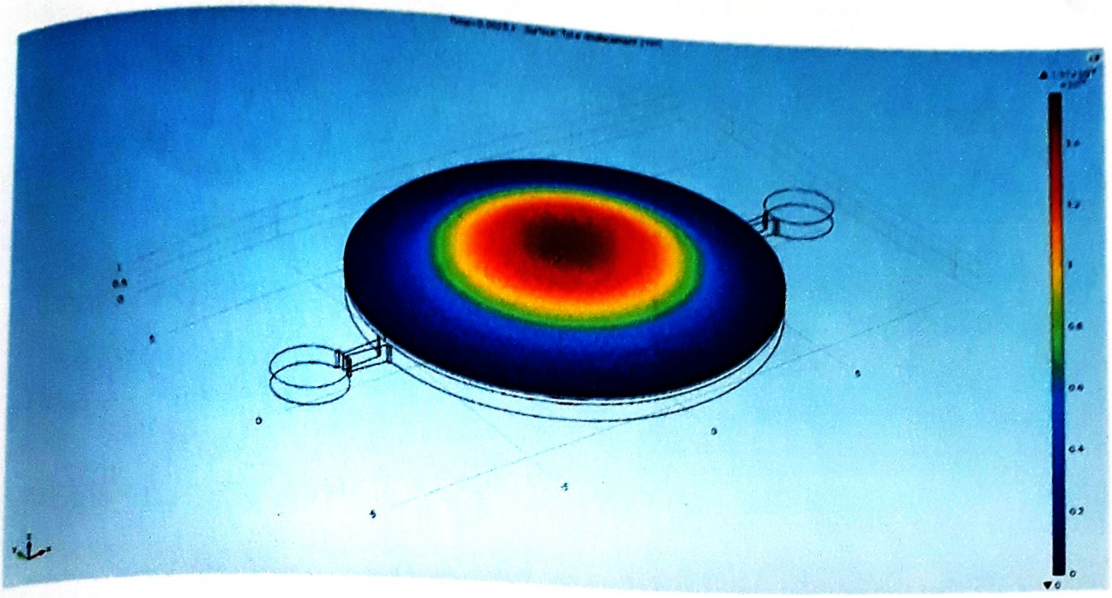


Fig. 4.5 Deflection of the diaphragm during supply mode (1.57 μm)

4.5.2 Pump Mode

During the pump mode, the diaphragm deflects in downward direction which increases the pressure of the fluid inside the chamber. As a result, the fluid from the chamber exits through the inlet and outlet. However, the fluid exiting from the outlet is more than the fluid exiting from the inlet as a result of the difference in the loss of the kinetic energy in the forward and reverse direction. Fig. 4.6 shows the Deflection of the diaphragm during Pump mode. Further, the difference in the pressure drop across the nozzle and diffuser elements during one cycle causes a flow rectification Pump Mode. Pump chamber diameter and depth are the two critical geometrical parameters which affect flow rate capability of the mechanical micropump.

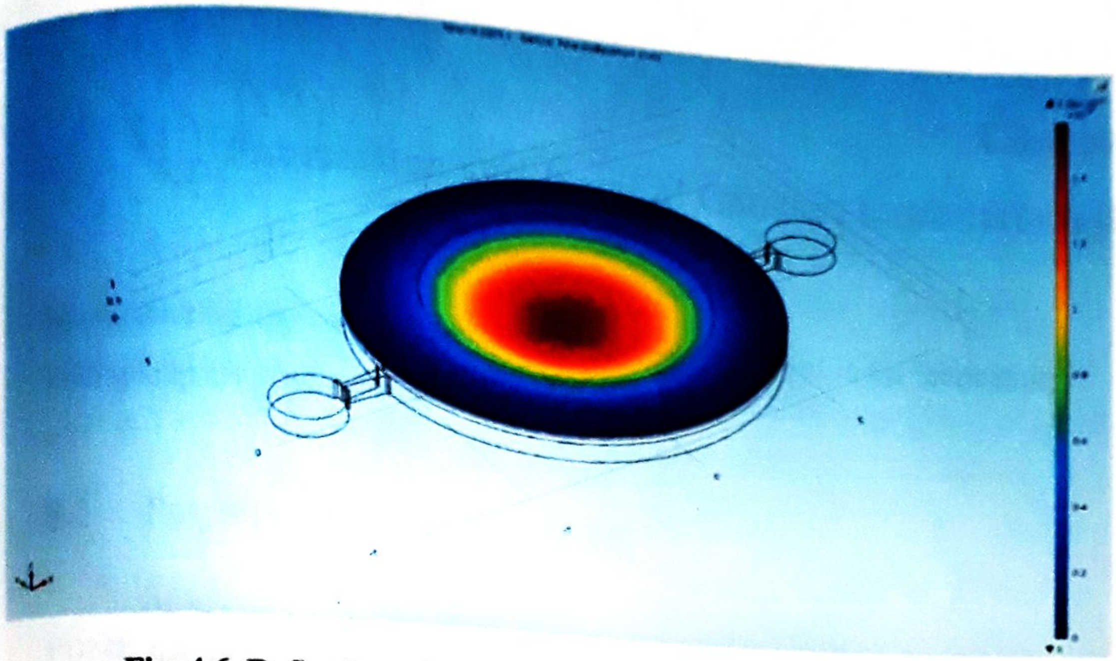


Fig. 4.6. Deflection of the diaphragm during pump mode (1.56 μm)

The variation in deflection of diaphragm as a function of time at 30 V with 100 Hz actuating frequency i.e. transient response of diaphragm deflection for two cycles is represented in Fig. 4.7. It is noted that the diaphragm deflection is more in supply mode as compared to the diaphragm deflection in pump mode. The maximum diaphragm deflection is 1.57 μm at 0.0025 s during supply mode. However, its magnitude is slightly decreased during pump mode and is 1.56 μm at 0.0075 s. This decrease in maximum diaphragm deflection during pump mode is due to the presence of the fluid within the pump chamber.

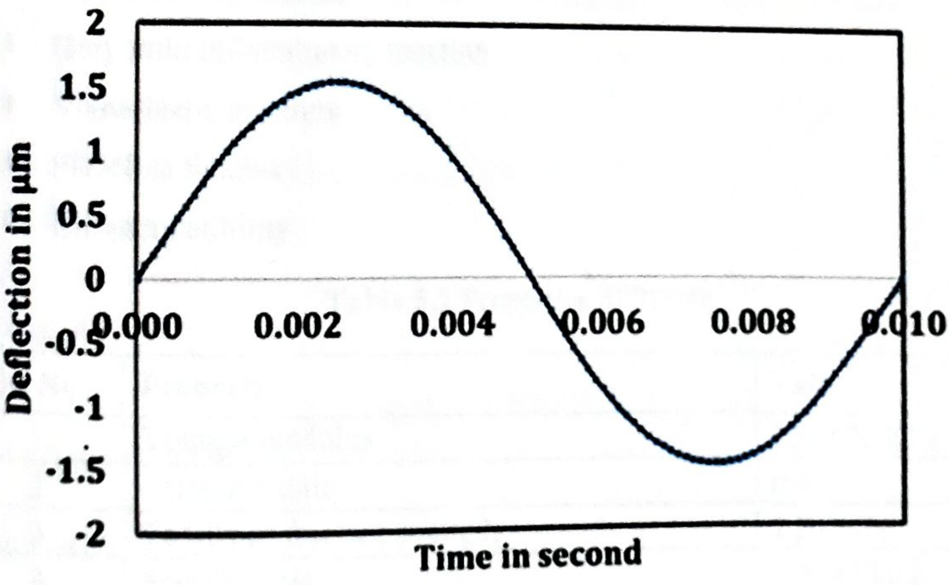


Fig. 4.7 Diaphragm deflection versus time during a cycle at actuation voltage of 30 V with actuation frequency of 100 Hz

Chapter 5

Fabrication and Proof of Concept Experimentation

Manufacturing approaches, methods and material employed in the fabrication of micropump are briefly described in this chapter.

5.1 Polydimethylsiloxane (PDMS)

PDMS has mechanical properties that make it suitable for microelectromechanical systems (MEMS). PDMS material could be applied to several types of microfluidic devices such as mixers, filters, channels, reactors, extractors, valves, flow sensors, droplets, and pumps. PDMS include operating systems size reduction, faster analytical and probability data, savings in the form of power reductions, broader design flexibility, and decrease in harmful byproducts. PDMS, a soft polymer, is being developed for use in microfluidics. Soft polymers of this caliber have advantages in the fabrication of MEMS devices.

5.1.1 Characteristics of PDMS

- Non-irritating to skin.
- Only mild inflammatory reaction
- Viscoelastic in nature
- PDMS is flexible
- Bio-compatibility

Table 5.1 Properties of PDMS

Sr. No.	Property	Value
1	Young's modulus	360-870 KPa
2	Poisson's ratio	0.49
3	Tensile or fracture strength	2.24 MPa
4	Specific heat	1.46 kJ/kg K
5	Thermal conductivity	0.15 W/mK
6	Dielectric constant	2.3-2.8

5.2 Advantages and Disadvantages of PDMS

- PDMS based microfluidic systems offer advantages over hard materials. Advantages include low cost and the time necessary to fabricate a small number of devices.
- The nature of PDMS allows for ease in modification and fabrication designs using soft lithography and replica moulding.
- The ability to produce compact sealing interfacing with optical fibres and inclusion of organic membranes were made easy through the use of soft lithography with PDMS.
- Other components or counterparts that are required to build functional devices are compatible with PDMS.
- At times some properties associated with PDMS may be affected when working with features less than twenty millimetres.
- Problems such as shrinking or sagging associated with PDMS can be eliminated with features greater than or equal to twenty millimetres.
- In the near future polymeric systems such as PDMS will replace glass and silicon systems for many biological analyses.
- Soft lithographic technology is expected to become more commercialized in the near future. Accompanying the projected commercialization of soft lithographic technology, the cost associated with current methods is expected to drop.

5.3 Polymethylmethacrylate (PMMA)

Polymethyl methacrylate (PMMA), also known as acrylic or acrylic glass, is a transparent and rigid thermoplastic material widely used as a shatterproof replacement for glass. PMMA has many technical advantages over other transparent polymer (PC, polystyrene etc.), few of them include:

- High resistance to UV light and weathering
- Excellent light transmission
- Unlimited colouring options

PMMA or poly (methyl 2-methylpropenoate) is produced from monomer methyl methacrylate. It is a clear, colourless polymer available in pellet, small granules and sheet forms, which are then formed with all thermoplastic methods (including injection moulding, compression molding, and extrusion). The highest quality PMMA sheets are produced by cell casting, but in this case, the polymerization and moulding steps occur concurrently. It is commonly called acrylic glass. The strength of the material is higher than moulding grades owing to its extremely high molecular mass. Rubber toughening has been used to increase the toughness of PMMA owing to its brittle behaviour in response to applied loads.

5.4 Piezoelectric Actuator

Piezoelectric (PZT) materials more generally, exhibit a unique range of properties. In a basic sense, if a piezoelectric material is deformed, an electric charge is generated in what is known as the piezoelectric effect. The opposite of this phenomenon also holds true: If an electric field is applied to a piezoelectric material, deformation occurs in what is known as the inverse piezoelectric effect. The lead zirconate titanate (PZT) transducer has been widely used as an actuator to pump fluid in the microfluidic application. By the diaphragm deformation caused by the PZT actuator, the induced volume change of pressure chamber makes the pumping effect possible. Among those PZT deformation modes, the common type is the extension one because it is easily poled and commercially available.

The material used for the construction of piezoelectric transducer requires high reliability, a wide frequency response range, and a linear response to applied voltage with reasonably low cost. The diaphragm is actuated due to piezoelectric effect induced in the PZT disc.

Table 5.2 Specification of employed PZT disc

Sr. No.	Parameter	Value
1.	Working Voltage	30 V
2.	Working Current	< 1mA
3.	Operating Temperature Range	10 °C to 70 °C
4.	Interface Type	Analog Output
5.	Size	12 mm
6.	Weight	5g

5.5 Manufacturing Method

5.5.1 Fabrication of Micro-Components

PDMS and PMMA are common materials for the fabrication of microfluidic devices for several reasons. First amongst many is the optical properties of these materials. The fabrication of PDMS/PMMA microfluidic device begins with a conceptual layout for a fluidic network.

5.5.2 Micropump Mold

The molds for rectangular wave micropump are manufactured using CO2 Laser engraving machine for fabricating master mold with steel. The manufactured micropump mold is characterized by Rapid-I Vision Measuring System.

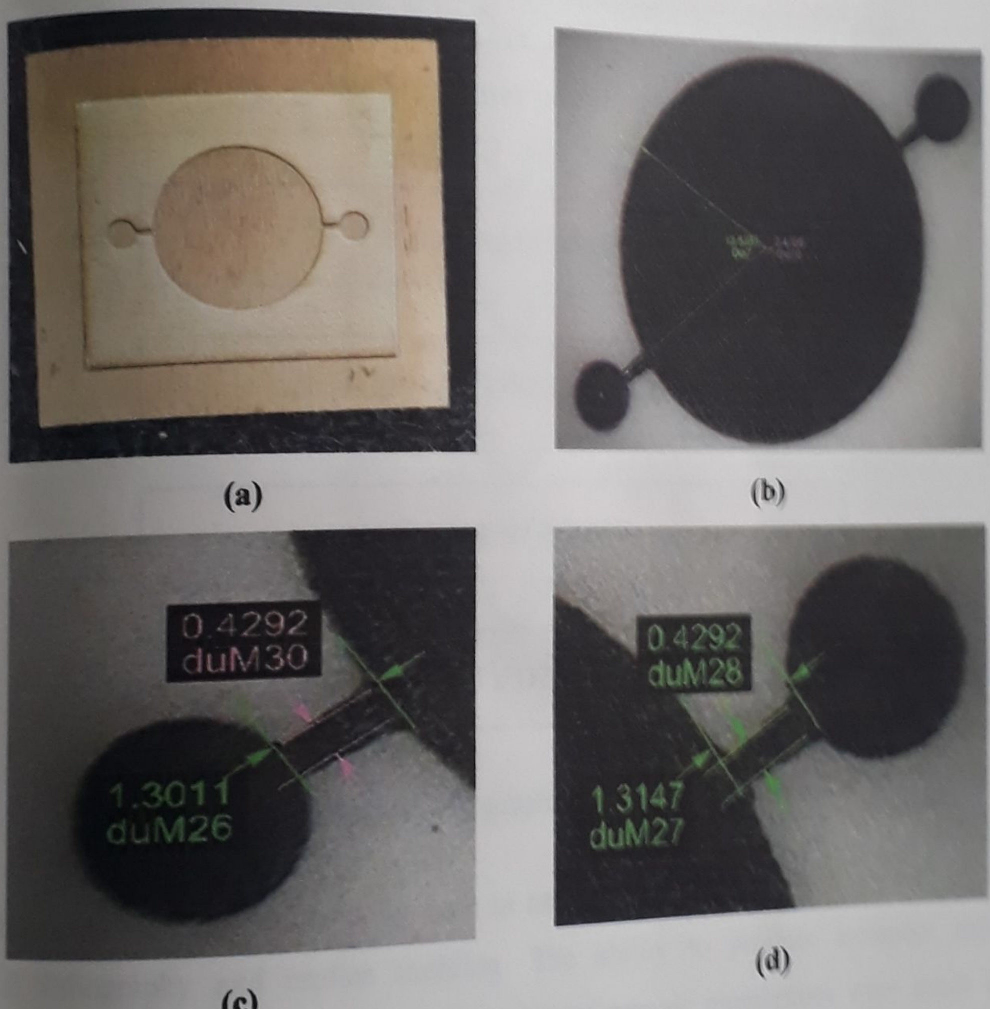


Fig. 5.1 Characterization of fabricated Micropump Components

The master mold and results of the characterization of the micropump mold for the dimensions of the pump chamber, inlet and outlet chambers, channel length, width and diffuser length are shown in Fig. 5.1. Characterization is done on colored photo tool using AutoCAD drawing in digital Printing.

5.5.3 Soft Lithography

PDMS microfluidic device fabrication is done easily with the use of soft lithography and rapid prototyping. Soft lithography is the technique used as a non-photolithographic technique for pattern replication and enables rapid prototyping of devices. The flow chart of soft lithography process are as follows:

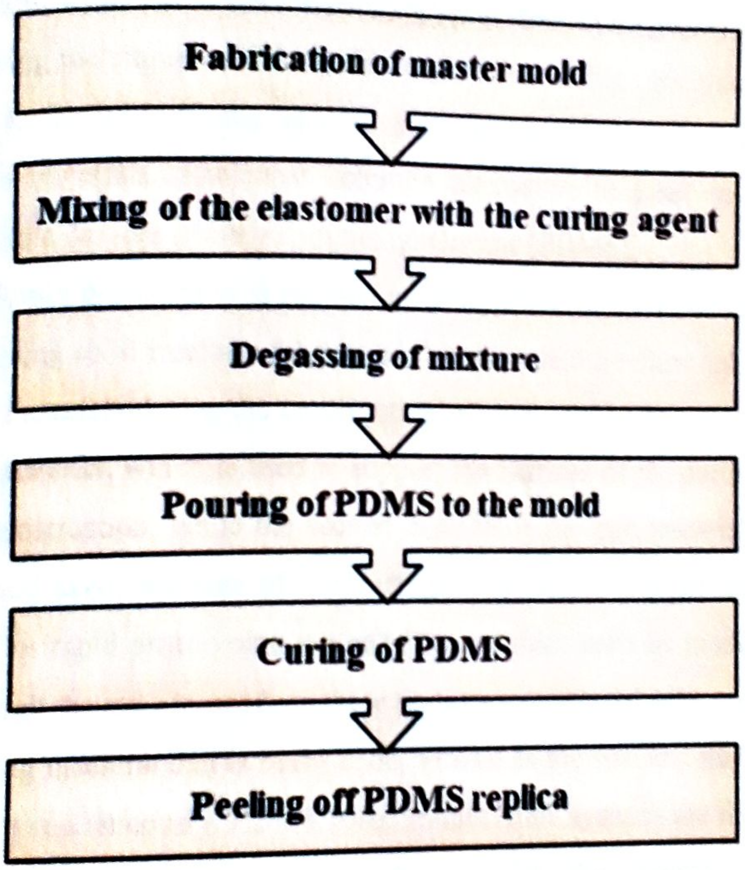


Fig. 5.2 Soft Lithography Process Flow Chart

The nature of PDMS allows for ease in modification and fabrication designs using soft lithography and replica molding. The ability to produce compact sealing interfacing with optical fibers and inclusion of organic membranes were made easy through the use of soft lithography with PDMS. A photoresist master mold can be created by standard lithographic techniques or any other technique and a liquid PDMS base solution with a curing agent is poured over the master. Due to the low surface tension of the PDMS solution, it readily flows and takes the shape of the master. The PDMS then cures and is peeled off as a negative impression of the master pattern. Soft lithography using elastomeric polymer molding in PDMS devices allows for rapid prototyping of microfluidic devices.

5.5.4 Rapid Prototyping Process

The second fabrication process involves Rapid Prototyping Machinery. Rapid prototyping is defined as being the automatic construction of physical objects using solid freeform fabrication. A particular rapid prototyping machine was utilized in the fabrication, which involves stereolithography. Stereolithography is a common rapid prototyping technique used for producing parts with high accuracy and good surface finish. A fabrication time can be significantly reduced by selecting alternative substrate materials. The most common alternative to glass in the fabrication of microfluidic devices is the polydimethylsiloxane (PDMS).

Rapid prototyping is defined as being the automatic construction of physical objects using solid freeform fabrication. Various solid freeform fabrication techniques use two materials during the construction of parts or models. The first material is the support material, which is used to support the features of the particular part or model during construction, while the second material is the part material. This depends on the method used, the size of the part, and the complexity of the model. Additive systems for rapid prototyping typically can produce parts or models in a few hours, even though the time to produce these parts can vary widely depending on the type of prototyping machine that is being used, as well as the size and number of parts being produced simultaneously. PDMS based microfluidic systems are fabricated by casting pre-cured polymer over a positive-relief mold of the intended micro- component geometry (microchannel) and allowing the polymer to cure. The resulting PDMS replica mold sticks with glass so that the fluidic microchannel can be sealed simply by contact bonding to a glass slide.

The PDMS is a two-part mixture (polymer and hardener/cure) with a ten to one ratio mixture. To give the PDMS a more solid and rigid structure, due to the fact that it will be undergoing mechanical stresses due to the electrostatic pump, silica (clay) particles were introduced into the PDMS mixture.

The PDMS was poured into the mold, the mixture was then poured into the mold that was developed in Fig. 5.4. The PDMS is then baked for approximately one hour between sixty-five degrees Celsius up to eight-five degrees Celsius. Fig. 5.3 indicates the views of Soft lithography. It was then left to cure for approximately twenty-four hours (or longer) to allow the PDMS polymer to chemically cross-link and form a solid structure. After it has cured it can be removed by peeling the PDMS away from the micropump mold.

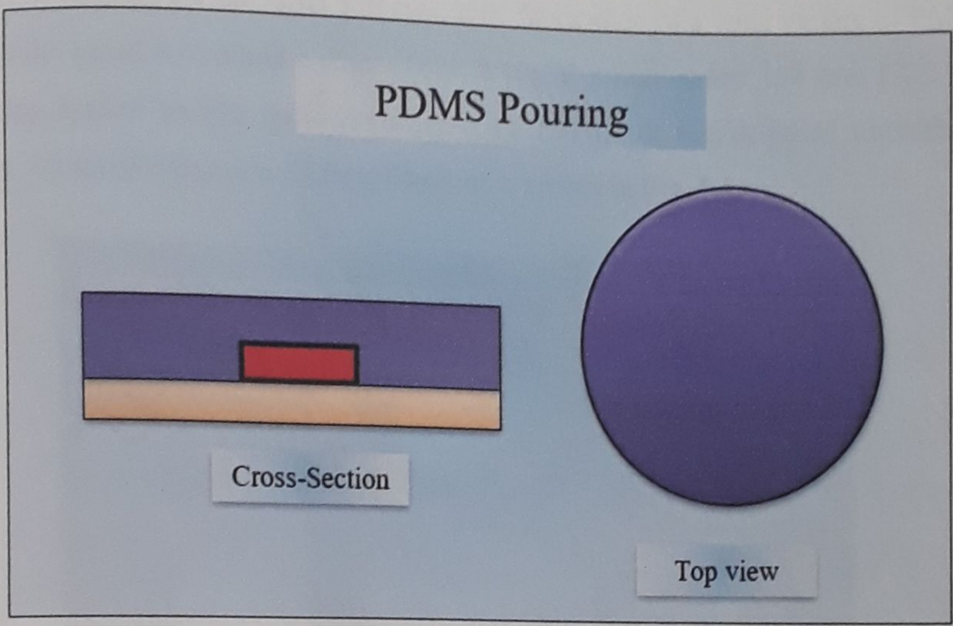


Fig. 5.3. Schematics of Soft lithography

(a) **(b)** **(c)**

Fig. 5.4 Photographs of steps involved in Soft Lithography (a) Sylgard 184 Silicone Elastomer (Manufacturer: Dow Corning), and (b) Simple Desiccator, (c) Pouring of PDMS solution.

5.5.5 CO_2 Laser Cutting Machining

A commercially available CO2 laser machine is used to perform the direct-writing ablation on acrylic substrates for microfluidic applications. It can also be used for cutting acrylic-based components. The microfluidic device designs are created using drafting software such as AutoCAD software and converted into the command signals required to drive the laser scriber in such a way as to reproduce the desired micro-component configuration on the surface of the acrylic substrate. Thus, it represents a practical solution for the rapid and economic fabrication of a wide variety of PMMA or acrylic based microfluidic chips. Thus, it can be a high-speed, low-cost CO2 laser scribing system for the rapid prototyping of PMMA or acrylic-based microfluidic chips. Set up of CO_2 Laser Cutting Machine is shown in Fig. 5.5.

Fig. 5.5 CO_2 Laser Cutting Machine

Table 5.3 Specification of CO_2 Laser machine

Parameter	Technical Details
Laser- type	Sealed CO2 laser tube, 2 inch focus lens
Laser power	60W
Engraving area	600 x 400 mm, 24" X 16"
Whole machine size	1,360 x 850 x 950 mm
Engraving speed	0 - 54,000 mm/min
Resetting position accuracy	± 0.05mm
Working voltage	AC 110 V ± 10%, 50 - 60Hz

5.6 Fabrication of Acrylic-based Components

Micropump functional layer and supporting layer required for PZT actuator are manufactured with acrylic material using CO_2 laser machining in our Advanced Manufacturing Laboratory.

The CO_2 laser machining has been used to fabricate support structure with acrylic material for the valveless micropump. The support structure is required to support the micropump and the actuator. The support structure consists of three acrylic plates. The top acrylic plate is placed over the micropump to hold the inlet and outlet tubing in position. The bottom acrylic plates are placed under the micropump to maintain the position of the actuator. The support structure of micropump including the top plate and bottom plate is as shown in Fig. 5.12.

5.6.1 Nozzle/Diffuser Element

The section of microchannel following the direction of the increase of cross-section area is called diffuser, while the section following the direction of decrease of cross-section area is called nozzle. Two nozzle/diffuser elements have the same geometrical dimensions. The diffuser and the nozzle are used as the inlet and outlet of the micropump chamber respectively. For easy integrating with other MEMS devices and high performance, the planar nozzle/diffuser element is used. At smaller divergence angle, the rectification efficiency is low as both nozzle and diffuser offer the same resistance and thus the net flow rate increases with increase in divergence angle. Similarly, at much higher divergence angles, the flow separation may occur which leads to the reduction in the net flow rate. Therefore, output of micropump also depends on the geometrical dimensions of the nozzle/diffuser element.

5.6.2 Pump Chamber

The pump chamber is the central section of the functional layer where fluid gets stored during suction mode and this stored fluid is forced to outlet during discharge mode. The diameter and depth of the chamber should be such that to conform to the diameter and the thickness of the piezoelectric actuator with sufficient space for storing fluid.

5.6.3 Diaphragm

The piezoelectric actuator consists of the piezoelectric disc and the thin elastic plate of brass material. Using AC voltage, the radial strain is generated in a piezoelectric disc which will cause the surface of the brass plate glued with the piezoelectric disc to bend. above Figure shows the structure of the diaphragm, which will be analyzed in two separate structures a tri-layer disk (PZT disk, glue/epoxy layer). Because the PZT disk is bonded to the epoxy, the radial expansion or contraction of the PZT disk makes the plate deflect upward or downward depending on the polarity of the voltage input. Consequently, deflection occurs in the PDMS diaphragm of a valveless micropump. the pumping effect of a bossed silicon diaphragm valve that was actuated periodically with the use of a piezoelectric bimorph.

The magnitude of deflection of diaphragm is small in comparison with the its diameter. A PZT disk attached on a diaphragm can oscillate the diaphragm as a function of the voltage input to the PZT disk. Fig. 5.6 shows the Acrylic-based component of micropump. The diaphragm oscillation changes the chamber pressure and moves the liquid along the channels connected to the chamber. Therefore, in order to properly evaluate the flow characteristics of a diaphragm micropump.

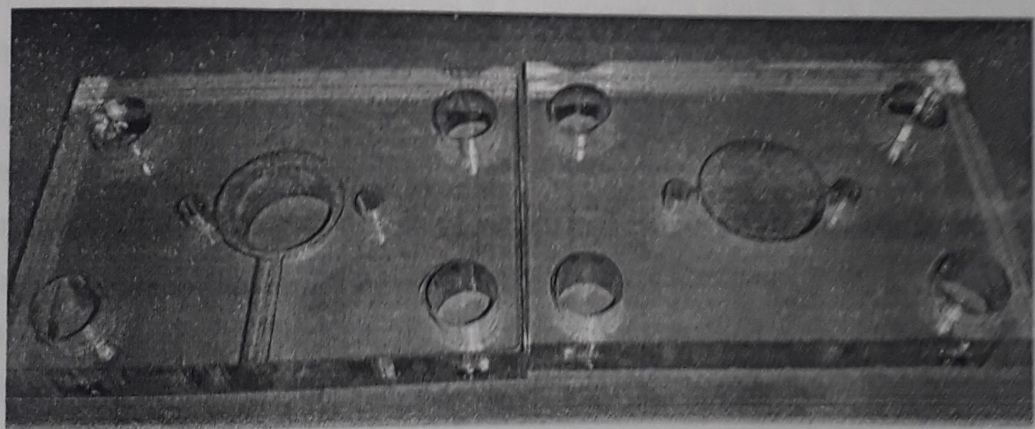


Fig. 5.6 Acrylic-based component of micropump (a) Left: Layer for supporting PZT and (b) Micropump functional layer

5.7 Fabrication of PCM-based micropump molds

Accordingly, the mask of micropump for X-ray lithography is fabricated on brass using UV lithography. Using UV lithography, pattern is transferred on resist coated brass or copper substrate. The mixture of ferric chloride and water are used for etching. The detailed process for mask preparation is described below:

- **Cleaning:** The organic or inorganic contaminations present on the thin sheet of copper and brass are removed by wet chemical treatment.
- **Coating:** A substrate of brass sheet of 100μm thickness is coated with a negative photoresist LPR.
- **Exposure:** The prepared substrate is exposed for the time of 2 min under UV source.
- **Development:** The substrate is developed in developer solution for the time of 1 min.
- **Etching:** Etching is carried out using FeCl3 solution.

The mask fabricated using UV Lithography are shown in Fig. 5.8. Photochemical Machining (PCM) process has originated from the knowledge of acid attack on metal. PCM process is combination of photoresist and chemical machining techniques. Photochemical machining is one of the chemical machining processes in which the photographic and chemical etching techniques are employed. This technology is relatively modern and got established as a manufacturing process. The photochemical machining process is mainly used to produce thin, complex, 2-D parts due to its ease of producing complex products with low cost and less delivery time apart from other advantage. The advantage of the process is the possibility to etch a wide range of materials such as metals, glasses or ceramics. The Copper is used as a substrate material for making master molds. However, the easiest metal to etch are copper, brass, steels, m, aluminum, and nickel (Fe, Ni, Co). procedure of PCM process are as follows:

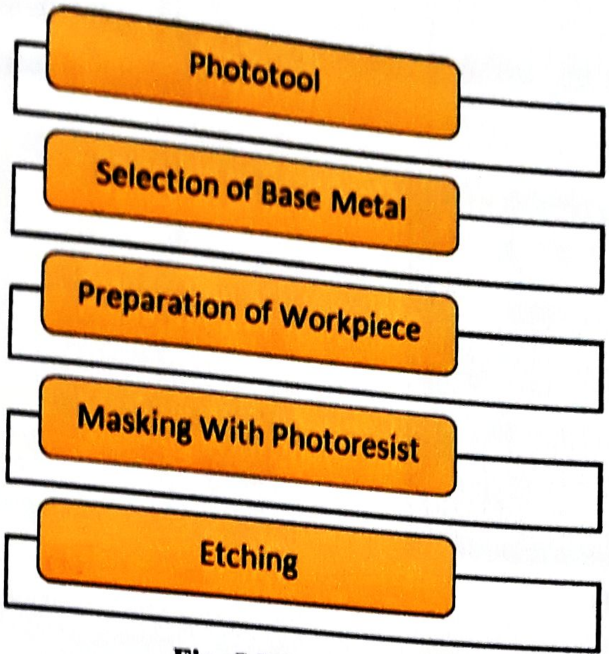
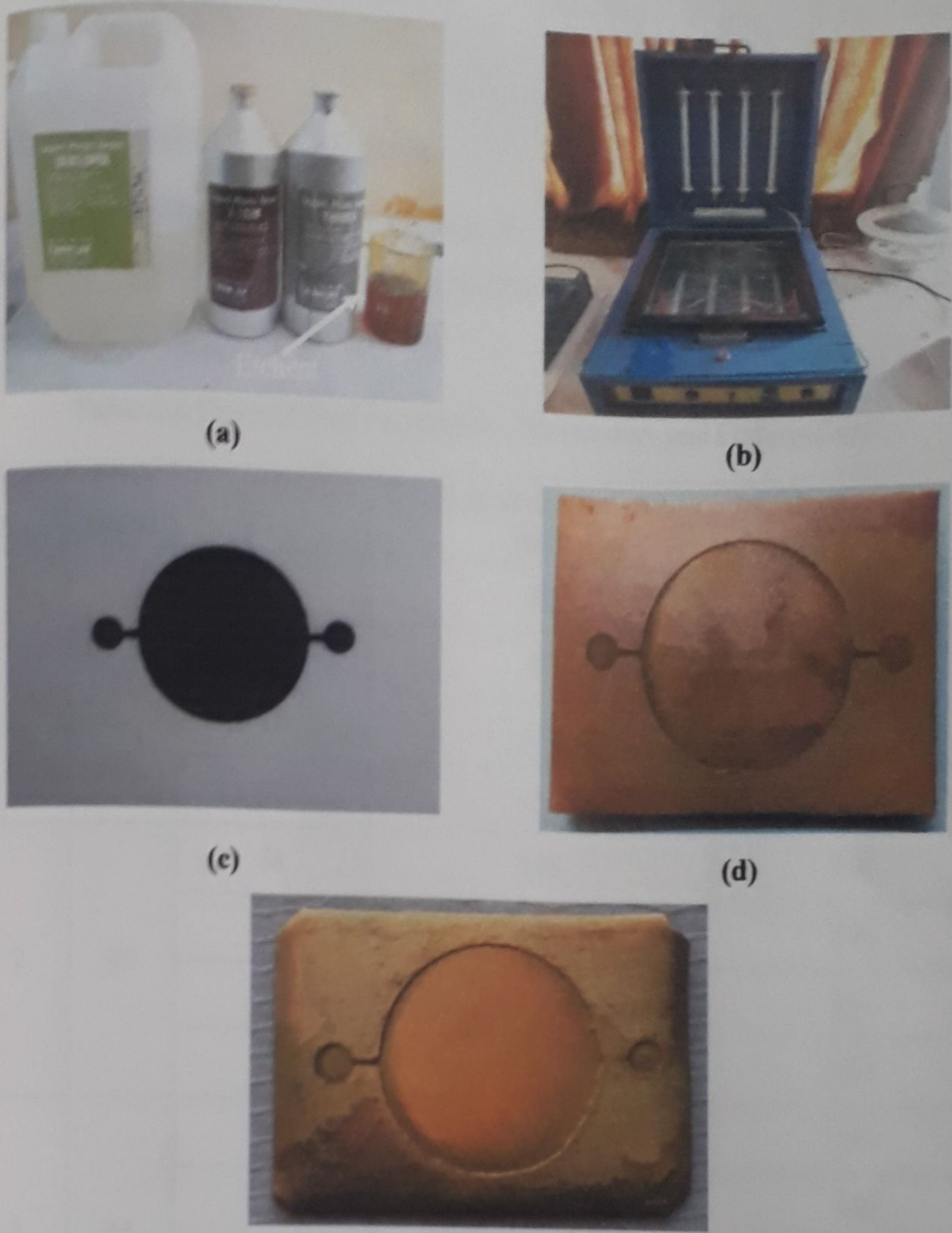


Fig. 5.7 PCM Process

The first step involved in PCM is to produce photo tool using AutoCAD drawing in digital printing. The sheet metals are chemically cleaned, and coats of a light sensitive photoresist coating applied on it. photoresist is in liquid form, and the part has to be dip coated and dried. Photo tools are used in precisely registered pairs like top and bottom. This photo tool arrangement permits the material to be etched on either side, which minimizes undercutting of photoresist. In next step the base meatal coated with the photoresist is then placed under the photo tool and exposed to an ultraviolet light source. Spraying on metal and develop the exposed image. Finally, depending upon process parameter we get desired depth of etched part or finished part is done [19].

Brass is an important material for various engineering applications, as because of its excellent electrical and thermal conductivity, easy fabrication, and good strength and fatigue properties. The Brass is the material used for this study, because it is more elastic after gold and aluminum. Photoresist chemical is blue coating ink. Developer NaOH solution and etchant of FeCl3. An aqueous solution of ferric chloride (FeCl3) is the most commonly used etchant. Materials used for this study are Brass and Copper. Photochemical machining has been carried out for copper and brass material. After machining, the edge deviation and the dimensions have been recorded with RAPID-I Vision 5 microscope. The depth of etching has been measured using the digital micrometer by calculating the volume of material removed (area x depth of etch) in mm3and dividing it by the respective etching time, the material removal rate has been evaluated (in mm^3/min.).



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

Fig. 5.8 Finished Component a) Photoresist Solution b) UV Exposing Unit c) Photo Tool Design d) Etched Micropump on Copper e) Etched Micropump on Brass

5.8 Comparison of Etching Depth for Brass and Copper

To get the precise size of the finished part by Photochemical machining process. The finished part is put under the RAPID-I machine and measures all dimensions like length, diameter etc. after the performing number of experiments we came to know that the material removal rate of copper is more as compared to brass. by performing experiments, we have obtain following optimum conditions:

- Temperature - 40^0C
- Time - 45 min
- Etchant Concentration - 500 gm/lit.

For etching on brass and copper material above temperature range are suitable for fabricating the design. Using the above optimum parameter, we have obtained proper etching depth about (40 to 500) micron.

Table 5.4 Experimental Reading for Temperature and Etching Depth

Sr. No.	Time (min)	Temperature (°C)	Depth of etching on brass (µm)	Depth of etching on copper (µm)
1	15	34	42	70
		36	80	95
		38	115	125
		40	152	164
2	20	34	148	200
		36	186	230
		38	220	261
		40	259	295
3	45	34	298	330
		36	335	368
		38	373	420
		40	408	470

The below Fig. 5.9 shows the etching depth of Brass and copper material with different time and temperature.

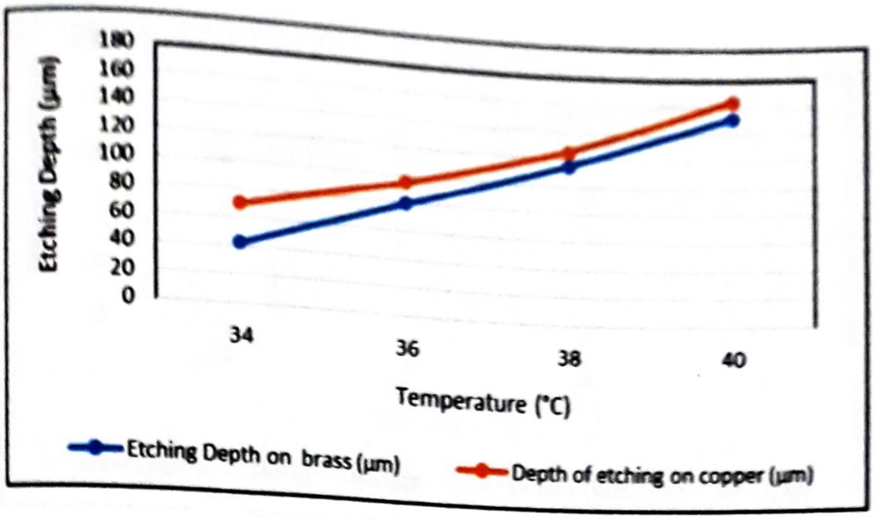


Fig 5.9 Etching Time – 15 (min)

The Fig. 5.10 shows the etching depth of Brass and copper material at different temperatures i.e. 34, 36, 38 and 40 °C respectively in 20 min.

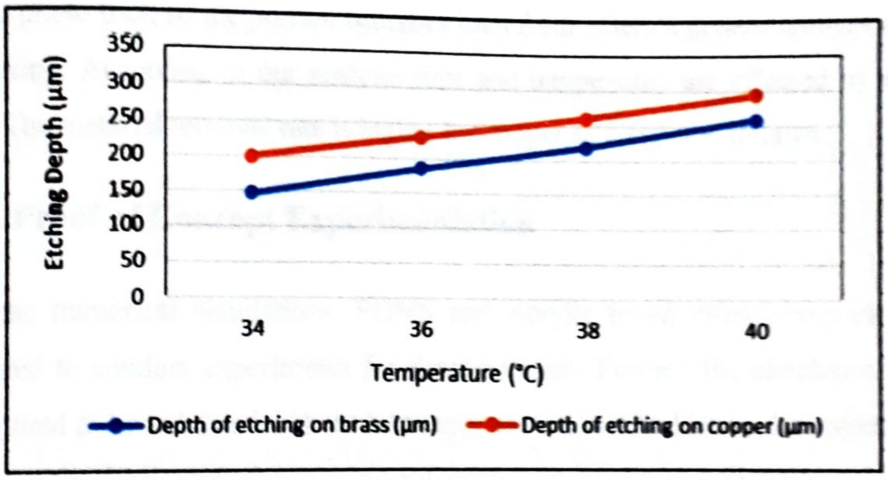


Fig. 5.10 Etching Time – 20 (min)

The Fig. 5.11 shows the etching depth of Brass and copper material at different temperature i.e. 34, 36, 38 and 40 °C respectively in 45 min.

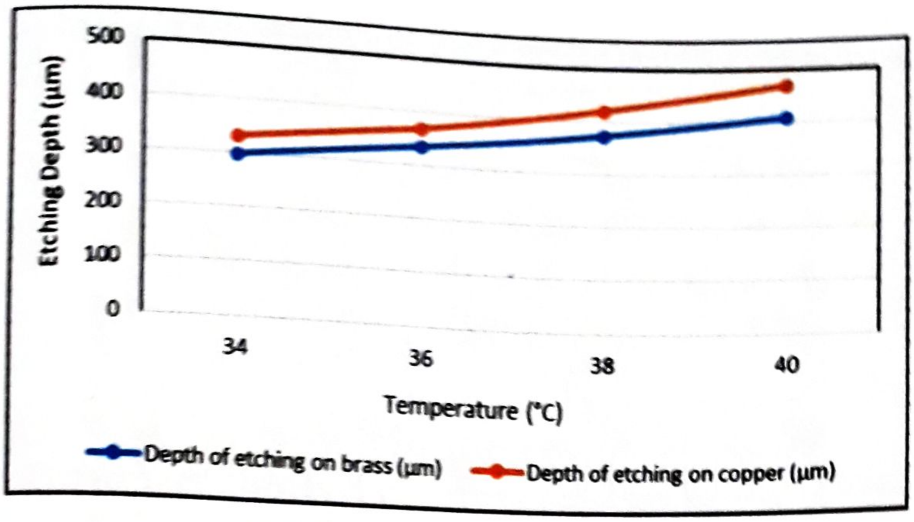


Fig. 5.11 Etching Time – 45 (min)

As the time increases from 15 min to 45 min etching depth increases accordingly. Fig. 5.9, 5.10 and 5.11 indicates the different etching depth with time for different temperatures. The negative photoresist is used and UV light passes through the colored photo tool, so the portion becomes hard from where a greater amount of light is traveling. According to our analysis time and temperature are affected by etching depth. The material removal rate is higher for copper as compared to brass.

5.9 Proof of Concept Experimentation

After the numerical simulations, PDMS and Acrylic based micro-components are fabricated to conduct experiments for demonstration. Further, the simulation results are required to be validated with the help experimental results. Hence, the experimental validation for fabricated piezoelectric actuation based valveless micropump has been carried out. The support structure consists of two acrylic plates and PDMS diaphragm. This diaphragm proper bonded between two acrylic plates. The top acrylic plate is placed over the micropump to hold the inlet and outlet tubing in position. The prototype fabricated at our in-house facility is shown Fig. 5.12.

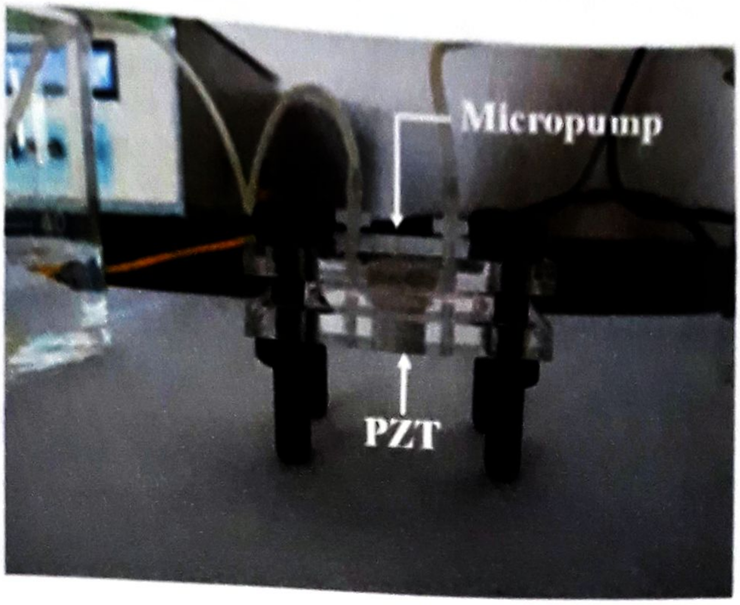


Fig. 5.12 Prototype of the piezoelectric actuation based micropump

5.9.1 Experimental Set-up

The different components of the micropump were manufactured by using methods already discussed. The micropump consists of two layers, viz. functional layer and diaphragm layer and support structure made-up of acrylic. The functional layer contains pump chamber, two diffuser/nozzle elements, inlet and outlet channels, and inlet and outlet. Whereas diaphragm layer contains permanent magnet glued to it.

Experimental setup for testing of the valveless piezoelectric actuation based micropump is depicted in Fig. 5.13 Piezoelectric power supply is used to generate the input sinusoidal voltage signal and frequency in the range 0-150 Hz. The output signal from the power supply was given to actuator for actuation. The inlet and outlet of the micropump are connected to two reservoirs (glass beakers) using silicone tubing with the inlet reservoir containing distilled water. The micropump chamber and the entire tubing are primed with distilled water prior to operation.

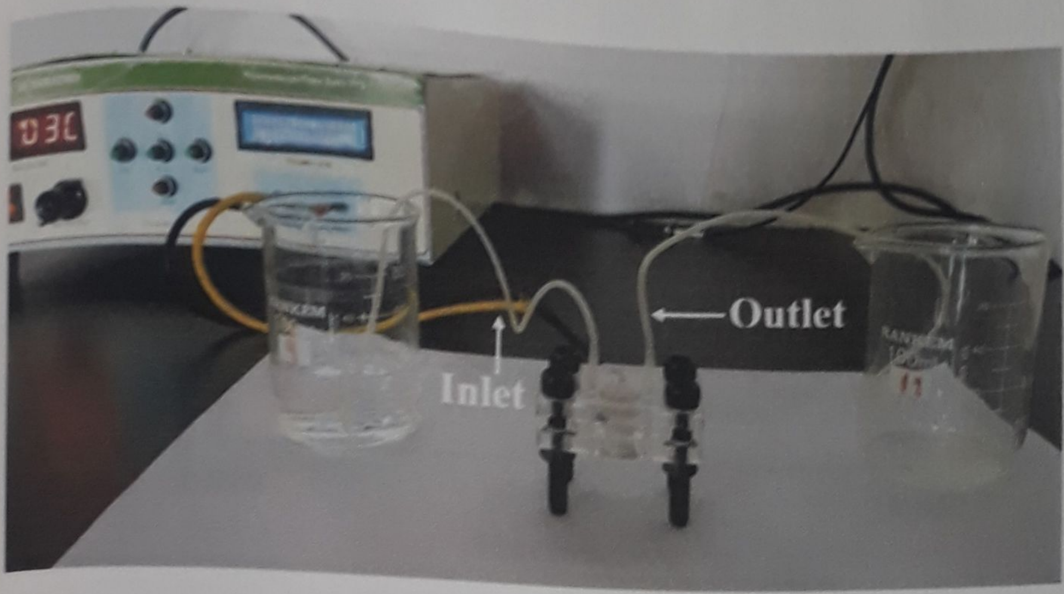


Fig. 5.13 Experimental setup for testing of a Piezoelectric actuation based Valveless micropump.

A flow rate of about 10 µl/min is measured at the actuation frequency (f) = 125 Hz. Experiment results show that, the proposed micropump is capable of delivering a flow rate of 10 µl/min at zero back pressure (Zero pressure head).

5.10 Results and Discussions

For validating results obtained through the simulations, the simulation results have been compared with the experimental results of the flow rate.

5.10.1 Flow Rate Through Simulation Study

The flow rectification can be clarified with the help of the transient response of flow rate through inlet and outlet during supply and pump modes as shown in Fig. 4.5 and Fig. 4.6. It clearly reveals that during the supply mode (Time period: 0 to 0.005 s), the fluid entering through the inlet (Q_+) into the pump chamber is more than the fluid entering through the outlet (Q_-) into the pump chamber. In contrast, during the pump mode (Time period: 0.005 to 0.01 s), the fluid leaving through the outlet (Q_+) is more than that of the fluid leaving through the inlet (Q_-).

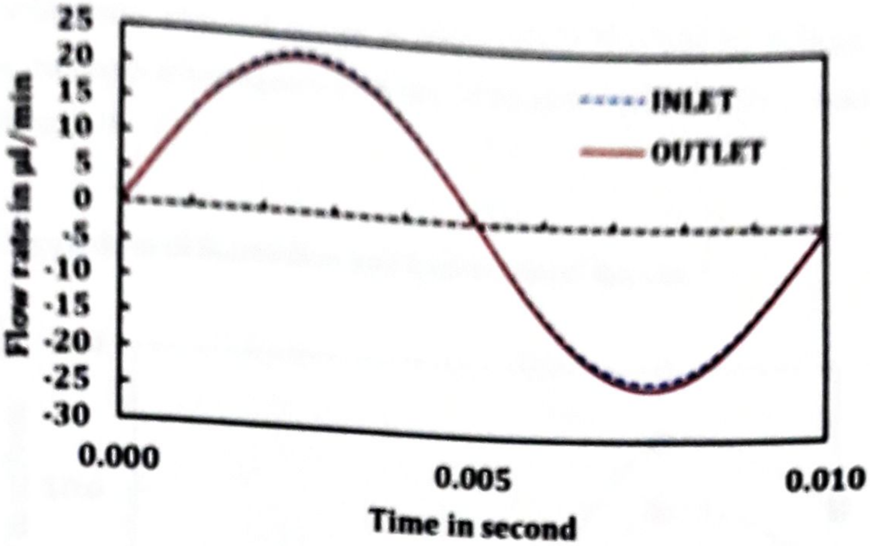


Fig. 5.14 Flow rate through the inlet and outlet as a function of time during cycle at actuation voltage of 30 V with actuation frequency of 100 Hz

The effect of the operating parameter, actuation frequency on the net flow rate needs to be studied to determine the required operating conditions to achieve the desired flow rate. The effect of actuation frequency of the sinusoidal voltage applied for during the numerical is studied numerically.

The flow rate result as a function of actuation frequency is depicted in Fig. 5.15. At the beginning, the flow rate increases with the increase in the actuation frequency. The flow rate reaches a maximum value of 10 µl /min at an actuation frequency of 125 Hz and beyond fact= 125 Hz, it goes on decreasing.

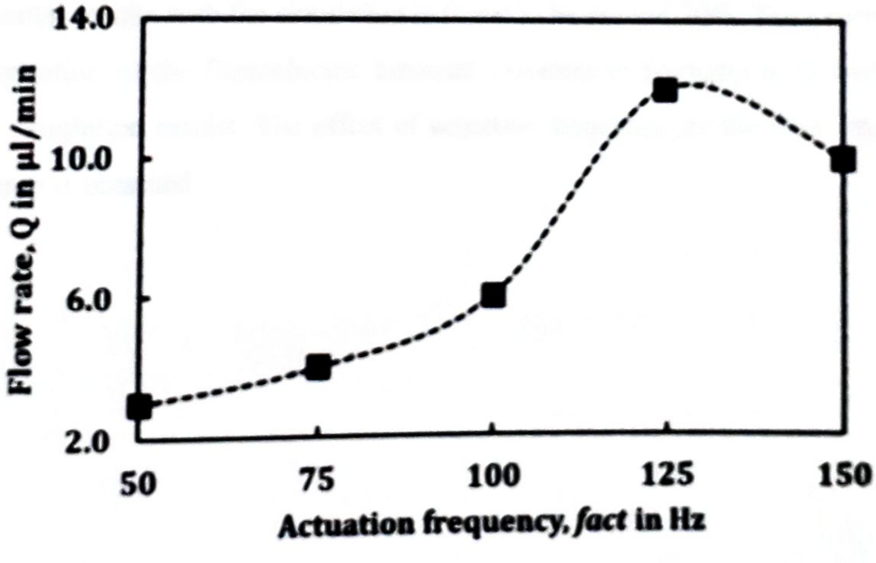


Fig. 5.15 Water flow rate as a function of actuation frequency at zero backpressure

The experimentally obtained results in terms of the flow rate as function of the actuation frequency are compared with that of the predicted using the simulations as shown in fig. 5.16.

5.10.2 Comparison of Simulation and Experimental Results

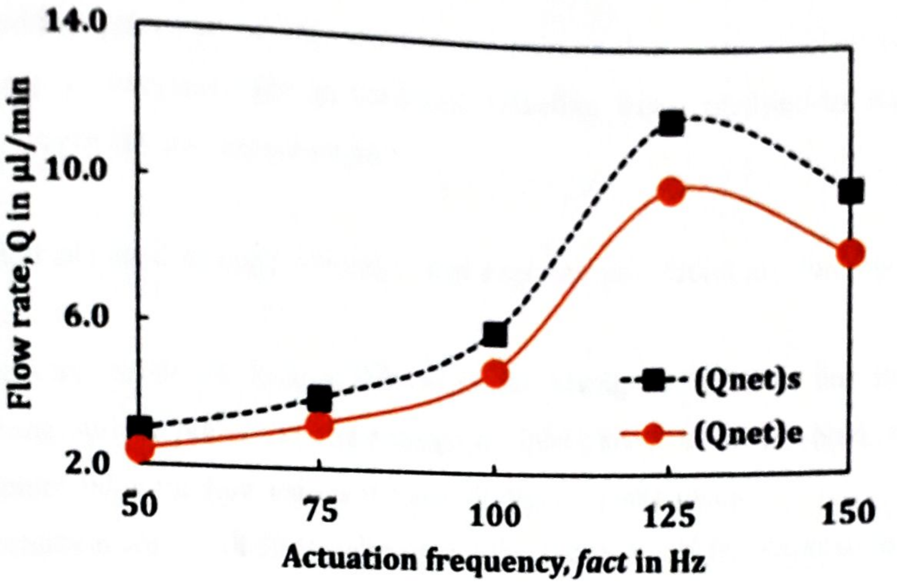


Fig. 5.16 Comparison between results obtained by simulation and experimental analysis.

It has been observed from the comparison depicted in Fig. 5.16 experimental results and simulation results for the flow rate have good agreement. The match between the experimental results with the simulation is found to be around 20%. The experimental characterization of the Piezoelectric actuated valveless micropump is carried out to validate simulation results. The effect of actuation frequency on the flow rate of the micropump is obtained.

Chapter 6

Conclusions and Future Scope

6.1 Conclusions

The working principle of piezoelectric micropump has been studied and the micropump is designed. The piezoelectric actuation based micropump has been studied numerically and experimentally.

The results obtained through simulation and experimental studies are summarized as follows:

1. Simulation results of flow at diffuser/nozzle configuration show that the flow entering into the pump chamber through the inlet during the supply mode is more as compared to the flow exiting the inlet during the pump mode.
2. At actuation voltage of 30 V and actuation frequency of 100 Hz, simulation results for total displacement of diaphragm show deflection of 1.57 µm and 1.56 µm during supply and pump mode, respectively.
3. At actuation voltage of 30 V and actuation frequency of 125 Hz, simulation results show the maximum flow rate of 12 µl/min at the outlet of micropump.
4. At actuation voltage of 30 V and actuation frequency of 125 Hz, experimental results show the maximum flow rate of 10 µl/min at the outlet of micropump.
5. The soft lithography technique can be used as one of the low-cost fabrication methods for fabricating PDMS based micro components used in microfluidic applications.
6. CO_2 laser is one amongst cheapest method for manufacturing the functional as well as supporting structures used in microfluidic applications.
7. PCM and CO_2 laser engraving can be used effectively for fabrication of moulds used in PDMS-based soft lithography.

6.2 Future Scope

Material selection for this micropump should be reviewed in order to select the compatible material for the specific application in biomedicine.

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