ON CHIP PLANAR CAPACITANCE TOMOGRAPH FOR TWO-PHASE
FLUID FLOW IMAGING

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S eciall dedicated to dea l athe and othe

eloved i lin

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ABSTRACT

Thi the i e ent the develo ent o an on-chi lana elect ical ca acitance to o a h ECT o two- ha e l id low i a in . Thi iniat i ed lana ECT device wa develo ed a ed on La -on-chi LOC o ic o l idic device conce t. Mic o l idic device i a o ta le device that inte ate di e ent la o ato activitie within a all lat o that handle ic o- cale l id and i no all ed o all a le e a ation i in and detection. To vi ali e the condition within the eaction cha e an e te nal o tical in t ent ch a ic o co e i ed ca in the device to e le o ta le. F the o e a ca e a that i attached to the o tical en o e i e la e e o o data to in and inten ive i a e oce in i needed to anal e the data ince it i eco ded a video. The e o e thi e ea ch o o e anothe o tion to ovide vi al i a e via lana elect ode a a whe e the elect ical data o tained can e to ed di ectl to a co te . Thi e ea ch inte ate to o a h techni e tili in ca acitance ea e ent within the ic o l idic device lat o o l id low ic oanal i o e . To econ t ct i a e ECT en o ea ed va iation in the e ittivit o a le within the en in a ea. Ei ht lana elect ode we e a icated on inted ci c it oa d with di en ion o 5.00 2.08 len th width di t i ted e all a o nd 16 dia ete o the en in a ea. Si lation t d wa cond cted in COMSOL M lti h ic to dete ine the de i n a a ete o ic o channel and ol di eth l ilo ane PDMS ic o channel wa a icated in ca tin ethod. The inte ation o lana elect ode en o to the PDMS ic o channel o ed the ic o device which allow two- ha e l id a le to low in and o t o the en in cha e . Fan ea o ection techni e wa ed o data collection ethod. A o twa e od le wa ilt in Mic o o t Vi al Ba ic and Linea Bac P o ection al o ith i i le ented o the i a e econ t ction oce . A o ta le data ac i ition DAQ te co i in o i nal conditionin nit and A d ino Me a ic ocont olle wa develo ed o online ea e ent. Two- ha e li id-ai and li id-li id a le we e t died. The a le we e lowed into the en in cha e at a con tant low ate. The econ t cted i a e we e co a ed to the eal i a e ca t ed the ca e a and the ea i ilit o the te o two- ha e l id low i a in wa t died. At a low ate o 12.03 l/ in the acc ac o the develo ed te in econ t ctin wate a le in wate -ai low ea e ent wa nea l 97.9 while the acc ac to econ t ct oil a le in wate -oil low ea e ent wa nea l 94.3 . The t d howed that the li id concent ation a ect i a e econ t ction a the e ittivit val e va ie with the li id concent ation. The econ t cted c o - ectional i a e howed ood e e lance with the c o ection o the ca e a ca t ed i a e . Thi e ea ch howed that the iniat i ed lana ECT te i ea i le to ca t e i a e o d na ic low tance within a en in cha e .

ABSTRAK

Te i ini e entan an e an nan at i te to o a i atah a a itan ele t i ECT ata ci nt en i e an ali an d a- a a. Pe anti atah ECT e ai ecil di ina e da a an on e *Lab-on-chip* LOC ata e anti i o l idi . Pe anti i o l idi adalah e anti dah alih an en inte a i el a ai a tiviti a al dala lat o ecil an en endali an cecai e ala i o dan ia an a di na an nt en ediaan e ca an dan en e anan a el ecil. Ba i en a a an eadaan dala an tinda ala in t en o ti l a an e e ti i o o di na an en adi an e anti te e t an dah alih. Selain it a e a an di a an ada en o o ti e e l an an e o i an e a nt en i anan data dan e o e an i e an inten i di e l an nt en anali i data e ana ia di e od e a ai video. Oleh it a ian ini encadan an en ediaan i e vi al da i ele t od atah di ana data ele t i al di i an te e dala o te . Ka ian ini en inte a i te ni to o a i en na an en an a a itan dala lat o e anti i o l idi nt t an i oanali i ali an cecai . Unt e ina e la i e e anti ECT en e ahan etel an a el dala awa an en o . La an ele t od atah di a i a i ada a an lita e ceta e di en i 5.00 2.08 an an le a di n e a a e ita awa an en e anan e dia ete 16 . Ka ian i la i di alan an den an COMSOL M lti h ic nt enent an a a ete e a ent al an i o dan al an i o *polydimethlsiloxane* PDMS di e a den an aedah en ac an. Inte a i ele t od atah dan al an i o PDMS e ent e anti i o dan e oleh an a el cecai d a a a en ali a dan el a da i an en e anan. Te ni n an al i a di na an e a ai aedah en a ilan data. Mod l e i ian di ina en na an *Microsoft Visual Basic* dan n an ali linea dila ana an a i o e en i e an e la. Si te e olehan data dah alih DAQ te di i da i ada nit en e aian i a at dan en awal- i o A d ino Me a di an n an a i en an ata talian. Sa el d a a a cecai - da a dan cecai -cecai telah di a i. Sa el diali an e dala awa an en e anan ada ada ali an teta . I e an di ina e la di andin an den an i e e ena ditan a da i ada a e a dan e olehla anaan i te nt en i e an ali an d a- a a telah di a i. Pada ada ali an 12.03 l/ in ete atan i te dala e ina e la a el ai di dala ali an ai - da a ehin a 97.9 e enta a ete atan i te dala e ina e la a el in a dala ali an ai - in a enca ai 94.3 . Ka ian en n an e e atan a el cecai e e i e an e ada i e an di ina e la e ana nilai etel an e e a den an e e atan cecai . I e e atan enta an di ina e la en n an e a aan an ai den an i e e atan enta an di e olehi en na an a e a. Ka ian ini en n an i te iniat atah ECT oleh dila ana an nt enan a i e ahan ali an dina i dala an en e anan.

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LIST OF ABBREVIATIONS

ADC	-	analo to di ital conve te
CT	-	Co te i ed To o a h
DAQ	-	data ac i ition te
ECT	-	Elect ical Ca acitance To o a h
EIT	-	Elect ical I edance To o a h
ERT	-	Elect ical Re i tance To o a h
FEM	-	inite ele ent ethod
	-	a e e econd
GUI	-	G a hical U e Inte ace
HR	-	h id econ t ction
ILBP	-	Ite ative Linea Bac P o ection
H	-	ilohe t
LBP	-	Linea Bac P o ection
LCR	-	Ind ctance Ca acitance Re i tance
LOC	-	la on chi
l/ in	-	illilit e e in te
MRI	-	Ma netic Re onance I a in
NMR	-	N clea Ma netic Re onance
PCB	-	inted ci c it oa d
PDMS	-	ol di eth l ilo ane
PET	-	Po it on E i ion To o a h
F	-	ico a ad
PT	-	P oce To o a h
RGB	-	ed een l e
R	-	eceive elect ode

S/	-	Sie en e ete
T	-	t an itte elect ode
USB	-	Unive al Se ial B
V -	-	volta e ea -to- ea

LIST OF SYMBOLS

A	-	act al i a e
a	-	hal a o the elect ode
$\mathbf{C}$	-	inte -elect ode ca acitance at i
C_f	-	eed ac ca acitance
C_x	-	ca acitive e on e
E	-	n e o elect ode
$E_{i/j}$	-	elect ic ield di t i tion
ε_r	-	dielect ic con tant
ε_o	-	elect ic con tant
$\mathbf{K}$	-	e ittivit at i
ℓ	-	len th o elect ode
M	-	n e o inde endent ea e ent
M	-	n e o individ al tandin ca acitance
N	-	n e o i el
R	-	econ t cted i a e
R_f	-	eed ac e i tance
$\mathbf{S}$	-	en itivit at i
$\mathbf{S}^{-1}$	-	inve e en itivit at i
$\mathbf{S}^{T}$	-	t an o e en itivit at i
w	-	width o the elect ode
ω	-	an la e enc
ϕ	-	otential di t i tion
θ	-	otation an le

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Microfluidic or lab on chip (LOC) has been introduced by Manz in 1990's o che ical a lication in li id ch o ato a h 1 . Since then it ha eco e a loo in technolo that i widel ed in io edical and che ical anal i edical dia no i and cell c lt in . LOC i a iniat i ed device that inte ate va io la o ato ie activitie ch a a le e a ation 2 DNA anal i 3 4 and ioche ical detection 5 within a in le chi . D e to the iniat e i e LOC device o e ene it ch a o ta ilit hi h th o h t and hi h detection en itivit . It in o t the o i ilitie o handlin an e t e el low l id vol e whe e eat ed ction in vol e con tion can e ade. The i e o LOC device a e no all in illi et e to a ew a e centi et e . The e o e it ini i e the con tion o ea ent the e ed cin ea ent o che ical ol tion wa ta e. Be ide LOC device ha the a ilit to ca o t a te anal i d e to hi h ace-to-vol e atio and ed ced eaction ti e which lead to ette oce cont ol co a ed to othe c ent anal tical ethod .

LOC device a e no all inte ated ic o channel with ic o eacto 6 ic o cha e ic o i e o e a ation col n o anal i . Va io t e o detection ethod have een e o ted the co on one a e in o tical en o o detectin d o let 7 and elect ode o elect ical o e tie ea e ent 8 . A the i e o the device ed ce to iniat e lat o inte ation o o tical en o i di ic lt and li ited. Hence econ t ctin i a e in elect ode i o e ve atile. Elect ode can e de i ned into va io i e and ha e acco din to the need o the detection. Va io ea e ent can e done in elect ode ch a elect oche ical detection 9 ca acitance o i edance ea e ent. Howeve o t o the ea e ent in elect ode a e ovidin 1D ea e ent and o ten e i e ca e a o eco din i a e . The e o e 2D data can e o tained inte atin to o a h techni e within the chi . Th c eatin 2D i a e it will enhance the a lication o LOC.

P oce to o a h PT i de ined a an a oach o o tainin c o - ectional i a e o an o ect witho t o t ctin the nat e o the oce ein e a ined. It ovide eal-ti e in o ation on the inte nal tate o oce in va io t e o en in a a o nted a o nd the e ion o inte e t. In ea lie wo PT i one o the en in techni e that have e ta li hed a o ida le e tation in edical ield o dia no i o e . In edical a lication the co te i ed to o a h CT can e X- a i a in to o tain c o - ectional i a e o h an od non-inva ivel . X- a and Ma netic Re onance I a in MRI e i ent i ed to dia no ed l n di o de and othe elevant to .

Since then a id develo ent o to o a h techni e ha een initiated and ha een a oved an lication and e e i ental wo that a e wo in . De endin on the a lication to o a h o e va io t e o en in ethod ch a elect o a netic adiation elect ical o e tie and aco tical o e tie . Elect ical to o a h i the o t o la to o a h te in ind t ial oce o low vi ali ation a it i non-inva ive and int in icall a e. Elect ical to o a h ea e the chan e o the elect ical ield di t i tion within the e ion o inte e t co ld e ca ied o t a ed on i edance ca acitance o e i tance ea e ent. A on va io to o a h odalitie elect ical ca acitance to o a h ECT ha een the o t cce l d e to the a id e on e ea e in a ication low co t and e i tance to hi h e e and te e at e.

Eithe in edical o oce ind t ie to o a h ha een ed in la e cale in oth ecto to date d e to thei h e and hi h vol e a le. Recent inte e t in the all cale detection a e the a lication o iniat i ed to o a h inc ea in l o la ove the la t ew ea . Howeve in ic oanal i o t o the en o ovide in le di en ional data whe e acc ate e ti ation i di ic lt to achieve. Th inte atin the to o a hic techni e into a alle lat o o e in o ation o detailed anal i ch a 2D i a e can e o tained.

1.2 Problem Statement

D e to the inc ea in a e o la on chi LOC o the a lication o l id onito in in cell ea e ent edical dia no i che ical and iolo ical anal i ic o l idic o LOC technolo ha een widel a lied. In ic o l idic the oce o cont ollin and ani latin all a o nt o l id i ca ied o t in a ic o channel o ic o eacto . A lot o edical and iolo ical anal i e i e contin o onito in o oce which i ti e con in in o de to have the whole oce to ta e lace. Fo e a le in cell c lt in oce the cell a e c ltivated nde acc atel cont olled condition ch a te e at e and H to aintain the con i tenc o c lt e condition. The d ation o cell owth i ti e con in de endin on the t e o cell and contin o onito in i needed to o e ve the cell la ehavio .

In cell c lt in the cell a e laced in a cell inc ato to ovide ta le the al condition. In conventional cell c lt in ic o co ic o e vation i the co onl ed ethod to o e ve the cell la activitie . Howeve it i di ic lt to t the ic o co e in ide the ic o inc ato d e to it l i e and the ic o cha e ha to e e oved o the inc ato o ic o co ic e a ination. An o tical in t ent ch a ic o co e i needed to ovide vi al i a e o the eaction ha ened within the ic o cha e . Mic o co e with ca e a e i e a h e data a e and la e to a e e o . The e o e thi e ea ch o o ed to inte ate elect ical lana to o a h en o into ic o l idic lat o to od ce i a e whe e the elect ical i nal data can e ea il to ed in the co te .

A a t o that o t o the detection in ic o device o ic oanal i ovide 1D data ill t ated in a a h o . Neve thele 2D to o a i i o tant in the a lication o cell detection io edical anal i o the lti ha e a le o e tie . The e 2D to o a hel in vi ali in the eal i a e o a le and o e acc ate e ti ation can e ade. With ic o a ication techni e iniat e en o a a can e inte ated in ide a ic o device. Thi ic o device with the en o a a act a a iniat e to o a h te that allow the e to o tain 2D data. The iniat i ed to o a h device will od ce 2D to o a that ill t atin the tate o the a le ein onito ed in the en in a ea.

1.3 Research Objectives

The ain ai o thi e ea ch i to t d the ea i ilit o a iniat i ed lana to o a h o two- ha e l id low i a in o e . The eci ic o ective o the e ea ch a e li ted a ollow :

1. To a icate an on-chi lana ca acitance to o a h o two- ha e l id low i a e econ t ction.
2. To inve ti ate the ea i ilit o lana elect ode nde d na ic low condition tili in inite ele ent ethod FEM and e e i ental a oach.
3. To develo a o ta le data ac i ition te that ovide online ea e ent o the iniat i ed lana ECT en o .

The ea i ilit o lana elect ode en o in oce to o a h i e lo ed. To acco li h the e o ective an 8- lana elect ode en o a ed on ca acitance ea e ent wa a icated and inte ated into ic o l idic lat o . Be ide a o ta le data ac i ition DAQ te and an i a e econ t ction o a tili in Linea Bac P o ection LBP al o ith wa develo ed o online onito in . Li id- a and li id-li id a le we e ed in thi e ea ch to te t the ea i ilit o the develo ed te in econ t ctin i a e o two- ha e l id low a le .

1.4 Research Scopes

The ea i ilit o iniat i ed lana ECT te o two- ha e l id low i a in i inve ti ated. Thi e ea ch i divided into device a ication the develo ent o data ac i ition te and o twa e od le develo ent o i a e econ t ction oce . The a ication o ic o device con i t o the a ication o lana elect ode a a the a ication o ol e - a ed ic o channel and the inte ation o low ele ent within the chi - a ed to o a h te .

The lana elect ode a a which i de i ned a ed on elect ical ca acitance to o a h i a icated on inted ci c it oa d PCB in the conventional etchin techni e. Meanwhile a ol e a ed ic o channel i a icated in ca tin ethod o a id otot in . A 3D a te te late i a icated to e ed a a old and ol di eth l ilo ane PDMS i ed a the ain ate ial o the a ication o ic o channel. A o ta le data ac i ition te co i in o i nal conditionin ci c it and A d ino Me a act a the cont olle nit o the ECT te . Thi DAQ te ea e the chan e in elect ical a a ete within the en in a ea. The te collect and condition the data e o e it i ent to the cont ol co te o i a e econ t ction oce .

A o twa e od le o i a e econ t ction i develo ed in Vi al Ba ic 6.0 to allow online i a in o two- ha e l id low a le . Linea Bac P o ection al o ith i i le ented o i a e econ t ction oce d e to it i le t ethod which allow a t co tational ti e. The econ t cted i a e a e ve i ied a ed on the eal ti e i a e ca t ed d in e e i ental wo . The alit o econ t cted i a e i anal ed a ed on i el- a ed anal i whe e the i a e i co a ed etween the eal and econ t cted i a e i el i el. F the e lanation on i el a ed ethod i di c ed in Cha te 5. Two- ha e l id low a le we e ed to te t the ea i ilit and the acc ac o the te .

1.5 Thesis Outlines

Thi the i con i t o i cha te . The i t cha te i the int od ction that contain o a ie ove view e a din on the e ea ch o ect. Thi cha te di c e on the ac o nd the o le to tac le the o ective and the co e o the e ea ch.

Cha te 2 oc e on eviewin the nda ental conce t and theo ie o oce to o a h . The a lication o la on chi technolo on oce to o a h a ed on evio t d i al o ein eviewed and the i a e econ t ction oce i e lained tho o hl .

Cha te 3 di c ed the i lation t d o the o ti al eo et o iniat i ed lana to o a h en o in inite ele ent ethod FEM . The a oach ed to a icate the lana en o and ic o channel a e di c ed in detail. The e eata ilit t d o the develo ed ic o device and the develo ent o DAQ te a e e ented.

Elect ical cha acte i ation o the develo ed te i e ented in Cha te 4. Thi cha te di c e the cha acte i ation o the te to ea e elect ical chan e in the l id low a le.

In Cha te 5 the i a e econ t ction o two- ha e l id low a le i e ented. The anal i o the i a e econ t ction o li id- a and li id-li id a le i di c ed a ed on the acc ac o the te . The detection a ilit o the te i e ented and di c ed.

Cha te 6 concl de the ove all e ea ch wo in thi the i . Si ni icant cont i tion o the e ea ch and idea o t e develo ent a e tated in thi cha te .

REFERENCES

1 Man A. G a e N. and Wid e H. M. Miniat i ed Total Che ical Anal i S te : A Novel Conce t o Che ical Sen in . *Sensors and Actuators B: Chemical*. 1990. 1 6 : 244-248.

2 Go ett D. R. Weave W. M. MacH A. J. H S. C. T e H. T. K. Lee W. A ini H. and Ca lo D. La el-F ee Cell Se a ation and So tin in Mic o l idic S te . *Analytical and Bioanalytical Chemistry*. 2010. 397 8 : 3249-3267.

3 D t e S. W. and o N. A. Mic o l idic -Ba ed La -on-Chi S te in DNA-Ba ed Bio en in : An Ove view. *Sensors*. 2011. 11 6 : 5754-5768.

4 han . Pa S. an S. and Wan T. H. An All-in-One Mic o l idic Device o Pa allel DNA E t action and Gene Anal i . *Biomedical Microdevices*. 2010. 12 6 : 1043-1049.

5 Li . Chen D. Lin I. H. A ott N. L. and Jian H. Mic o l idic Sen in Device E lo in In Sit - o ed Li id C tal Thin Fil o Detection o Bioche ical Inte action . *Lab Chip*. 2012. 12 19 : 3746-3753.

6 Ped o S. G. Ma t ne -Ci ne o C. S. P ol M. and Alon o-Cha a o J. Mic o eacto with Inte ated Te e at e Cont ol o the S nthe i o CdSe Nanoc tal . *Lab on a chip*. 2012. 12 11 : 1979-1986.

7 K wandi B. N i an H en J. and Ve oo W. O tical Sen in S te o Mic o l idic Device : A Review. *Analytica Chimica Acta*. 2007. 601 2 : 141-155.

8 D'hahan, N. P. Live Cell Analysis: When Electric Detection Interfaces Mic o l idic . *Journal of Biochips & Tissue Chips*. 2011. S1: 1-9.

9 Collie W. A. and Ha t A. L. Elect oche ical Detection in Mic o l idic Device . *International Conference on Sensing Technology*. Nove e 21-23 2005. Pal e ton No th New ealand. 2005. 589–593.

10 Reinec e N. and Mewe D. Recent Develo ent and Ind t ial / Re ea ch

A lication o Ca acitance To o a h . *Measurement Science Technology*. 1996. 7 3 : 233-246.

11 D a ow i T. P oce To o a h A lied to M lti- ha e Flow Mea e ent. *Measurement Science and Technology*. 1996. 7 3 : 343-353.

12 I ail I. Ga io J. C. B ha i S. F. A. and an W. Q. To o a h o M lti- ha e Flow Mea e ent in the Oil Ind t . *Flow Measurement and Instrumentation*. 2005. 16 2 : 145-155.

13 Rahi R. A. *High Speed Data Acquisition System for Computer Tomographic Imaging Instrumentation*. Mala ia: Unive iti Te nolo i Mala ia P e . 2005.

14 Bec M. S. and Willa R. M. P oce To o a h : a E o ean Innovation and it A lication . *Measurement Science Technology*. 1996. 215 7 : 215-224.

15 I ahi S. G een R. G. D tton K. Evan K. Rahi R. A. and Go de A. O tical Sen o Con i ation o P oce To o a h . *Measurement Science and Technology*. 1999. 10 11 : 1079-1086.

16 Din S. M. *Segmented Excitation for Electrical Capacitance Tomography*. Ma te The i . Unive iti Te nolo i Mala ia 2014.

17 Ro S. and Band o adh a S. K. Detection and Q anti ication o B ain Tumor from MRI of Brain and it's Symmetric Analysis. *International Journal of Information and Communication Technology Research*. 2012. 2 6 : 477-483.

18 Mo at B. A. Cheneve t T. A. Law ence T. S. Me e C. R. John on T. D. Don Q. T ien C. M he i S. Q int D. J. Ge a i S. S. Ro e t on P. L. J nc L. R. Rehe t lla A. and Ro B. D. F nctional Di ion Map : A Noninvasive MRI Bio a e o Ea l St ati ication o Clinical B ain T o Re on e. *Proceedings of the National Academy of Sciences of the United States of America*. 2005. 102 6 : 5524-5529.

19 Mo ow M. Wate J. and Mo i E. MRI o B ea t Cance Sc eenin Dia no i and T eat ent. *Lancet*. 2011. 378 9805 : 1804-1811.

20 Malet-Ma tino M. and Hol a e U. NMR Techni e in Bio edical and Pha ace tical Anal i . *Journal of Pharmaceutical and Biomedical Analysis*. 2011. 55 1 : 1-15.

21 Bonn D. Rodt S. G oenin M. Ra a S. Shahid adeh-Bonn N. and

Co ot P. So e A lication o Ma netic Re onance I a in in Fl id Mechanic : Co le Flow and Co le Fl id . *Annual Review of Fluid Mechanics*. 2008. 40 1 : 209-233.

22 M lle C. R. Holland D. J. Sede an A. J. Mantle M. D. Gladden L. F. and David on J. F. Ma netic Re onance I a in o Fl idi ed Bed . *Powder Technology*. 2008. 183 1 : 53-62.

23 Rahi an M. H. F. Rahi R. A. Rahi an M. H. F. and Ta din M. Ult a onic T an i ion-Mode To o a h I a in o Li id / Ga Two-Pha e Flow. *IEEE Sensors Journal*. 2006. 6 6 : 1706-1715.

24 Waha . A. Ah ad M. A. Rahi R. A. and Rahi an M. H. F. A lication o T an i ion-Mode Ult a onic To o a h to Identi M lti ha e Flow Re i e. *ECCE 2011 - International Conference on Electrical, Control and Computer Engineering*. J ne 21-22 2011. Pahan Mala ia: IEEE. 2011. 119–123.

25 M ha ad I. R. Waha . A. and Saat S. Identi ication o Wate / Solid Flow Re i e U in Ult a onic To o a h . *IEEE International Conference on System Engineering and Technology*. Se te e 11-12 2012. Band n Indone ia: IEEE 2012. 3–7.

26 an W. Q. and Lih i P. I a e Recon t ction Al o ith o Elect ical Ca acitance To o a h . *Measurement Science and Technology*. 2003. 14 1 : R1-R13.

27 D o E. and Woodha R. J. Co inin Line and Point Co e ondence o Ho o a h E ti ation. In: Be i G. et al. ed . *Advances in Visual Computing. ISVC 2008*. Lect e Note in Co te Science. Heidel e : S in e -Be lin. 202-213 2008.

28 Wol D. L A. Rode F. and Lichte H. Elect on Holo a hic To o a h . *Current Opinion in Solid State and Materials Science*. 2013. 17 3 : 126-134.

29 David on J. L. R ino L. S. Ste hen on D. R. Mann R. G ieve B. D. and o T. A. Th ee-di en ional Elect ical I edance To o a h A lied to A Metal-Walled Filt ation Te t Plat o . *Measurement Science and Technology*. 2004. 15 11 : 2263-2274.

30 han W. Wan C. an W. and Wan C. H. A lication o Elect ical Ca acitance To o a h in Pa tic late P oce Mea e ent – A Review.

Advanced Powder Technology. 2014. 25 1 : 174-188.

31 Moha ad E. J. Rahi R. A. Rahi an M. H. F. A e an H. L. M. M i S. . M. and Ma wah O. M. F. Mea e ent and Anal i o Wate /Oil M lti ha e Flow in Elect ical Ca acitance To o a h Sen o . *Flow Measurement and Instrumentation*. 2016. 47: 62-70.

32 Moha ad E. J. n F. R. M. Rahi R. A. and Chan K. S. Ha dwa e Develo ent o Elect ical Ca accitance To o a h o I a in a Mi t e o Wate and Oil. *Jurnal Teknologi (Sciences and Engineering)*. 2011. 54: 425-442.

33 Moha ad E. J. Ma wah O. M. F. Rahi R. A. Rahi an M. H. F. and M i S. . M. Elect onic De i n o Po ta le Elect ical Ca acitance Sen o : A M lti ha e Flow Mea e ent. *4th International Conference on Mechatronics (ICOM)*. Ma 17-19. 2011. K ala L Mala ia: IEEE. 2011. 1–8.

34 Jawo i A. J. and Bolton G. T. The De i n o an Elect ical Ca acitance To o a h Sen o o U e With Media o Hi h Dielect ic Pe ittivit . *Measurement Science and Technology*. 2000. 11 6 : 743-757.

35 Wa ito W. and Fan L. S. Mea e ent o Real-Ti e Flow St ct e in Ga –Li id and Ga –Li id–Solid Flow S te in Elect ical Ca acitance To o a h ECT . *Chemical Engineering Science*. 2001. 56 21 : 6455-6462.

36 Ga io J. C. A Co a ative Anal i o Sin le- and M lti le-elect ode E citation Method in Elect ical Ca acitance To o a h . *Measurement Science and Technology*. 2002. 13 12 : 1799-1809.

37 . Ren *Exploration of Medical Applications of Electrical Capacitance Tomography*. PhD. The i The Unive it o Manche te 2015.

38 Qai e A. De i nin a Ca acitive Sen o in COMSOL. 2010.

39 Moha ad E. J. and Rahi R. A. M lti ha e Flow Recon t ction in Oil i eline Po ta le Ca acitance To o a h . *2010 IEEE Sensor*. Nove e 1-4 2010. Kona Hawaii IEEE 2011. 273–278.

40 an W. Li . W . T a a i D. Lea onth D. Xie C. G. H an S. Lenn C. and C tle A. M lti ha e Flow Mea e ent Elect ical Ca acitance To o a h . *IEEE International Conference on Imaging Systems and Techniques (IST)*. Ma 17-18 2011. Penan Mala ia IEEE.

2011. 108–111.

41 G t . Wolan i P. and Ole c a P. Monito in o Co tion P oce e in Ind t ial B ne in Elect ical Ca acitance To o a h . *Journal of KONES Powertrain and Transport*. 2011. 18 3 : 117-121.

42 F F. Kon M. X C. Lian C. and Wan S. Flow Cha acte i ation o Den e- ha e Pne atic Conve in S te o P lve i ed Coal Th o h Elect o tatic Sen o A a . *Advances in Mechanical Engineering*. 2013. 5: 1-13.

43 an W. Q. Ha dwa e De i n o Elect ical Ca acitance To o a h S te . *Measurement Science and Technology*. 1996. 7 3 : 225-232.

44 o T. Stat o Elect ical To o a h in Ind t ial A lication . *Journal of Electronic Imaging*. 2001. 10 3 : 608-619.

45 T a t i N. Ni oleli G. Va a a T. Ni oleli D. P. P cho io V. N. P a o da i N. and Lioda i S. La -on-a-Chi and Mic o l idic Technolo . *Portable Biosensing of Food Toxicants and Environmental Pollutants*. CRC P e . 2013. 395–410.

46 P a ad S. adav . K nd V. Botha a M. and M th a S. La -on-a-Chi . *Physics of Accessory Medicine*. CRC P e . 2010. 41 1 -41 7 .

47 Li . and Li X. Mic o l idic and La -on-Chi Technolo ie o Bio en o . *Biosensor Based on Nanomaterials and Nanodevices*. CRC P e . 2013. 443–478.

48 Va a P. Wood C. L. Schl e D. J. and Sho o hi S. RatCAP: Miniat i ed Head-Mo nted PET o Con cio Rodent B ain I a in . *IEEE Transactions on Nuclear Science*. 2004. 51 5 : 2718-2722.

49 Pitithee a a . Chanwi al ean T. Pintavi oo C. and To anon P. Miniat ed Co ted To o a h S te and Cali ation. *IEEE Conference on Industrial Electronics and Applications*. Ma 24-26 2006. Sin a o e IEEE. 2006. 4-8.

50 Ti ean I. C aci ne c T. and Mandache B. N. Non-De t ctive Anal i o Miniat i ed F ion Mate ial Sa le and I adiation Ca le X- a Mic o-to o a h . *Fusion Engineering and Design*. 2005. 75: 1055-1059.

51 in J. Li X. Jin J. Li J. M ai D. Mahon S. Ed i A. Hoan K. Sh n K. K. B enne M. Na la J. ho Q. and Chen . Novel Co ined Miniat e O tical Cohe ence To o a h Ult a o nd P o e o In

Vivo Int ava c la I a in . *Journal of Biomedical Optics*. 2011. 16 6 : 60505-0-60505-3.

52 Willia R. A. Ni et A. Dic in F. and Ta lo S. Mic oelect ical To o a h o Flowin Collodial Di e ion and D na ic Inte ace . *The Chemical Engineering Journal*. 1995. 56 3 : 143-148.

53 G i ith H. T c e M. G. Sa e J. and He enden-Ha e W. G. An Elect ical I edance To o a h Mic o co e. *Physiological Measurement*. 1996. 17 4A : A15-A24.

54 Linde hol P. Ma e cot L. Lo e M. H. and Rena d P. Cell C lt e I a in U in Mic oi edance To o a h . *IEEE Transactions on Biomedical Engineering*. 2008. 55 1 : 138-146.

55 S n T. T da S. a ne K. P. and Mo an H. Sin le Cell I a in in Elect ical I edance To o a h . *4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems*. Jan a 5-8 2009. Shen en China: IEEE 2009. 858–863.

56 S n T. T da S. a ne K. P. and Mo an H. On-chi Elect ical I edance To o a h o I a in Biolo ical Cell . *Biosensors & Bioelectronics*. 2010. 25 5 : 1109-1115.

57 o T. A. Evan I. G. Po ev i . and D a ow i T. Ca acitance Sen o o Mic o I a in . *Proceeding of SPIE*. 2001. 4188: 251-260.

58 Evan I. and o T. Mic oelect onic Ca acitance T an d ce o Pa ticle Detection. *IEEE Sensors Journal*. 2004. 4 3 : 364-372.

59 o T. S n L. G e o C. and Hat ield J. Silicon- a ed Miniat e Sen o o Elect ical To o a h . *Sensors and Actuators A: Physical*. 2004. 110 1 : 213-218.

60 o T. A. Ph a T. N. Reichelt L. Pawlow i A. and Knee R. A Miniat e Elect ical Ca acitance To o a h. *Measurement Science and Technology*. 2006. 17 8 : 2119-2129.

61 Ph a T. N. and o T. Wea -Inve ion Mea e ent Ci c it o Miniat e Elect ical Ca acitance To o a h . *IEEE Transactions on Instrumentation and Measurement*. 2008. 57 2 : 379-385.

62 A i A. Rahi R. A. Chee P. S. Din S. M. M a i N. A o N. and Leow P. L. Miniat i ed Plana Sen o Develo ent. *Jurnal Teknologi*. 2014. 8: 101-105.

63 A i A. *Miniaturized Planar Capacitance Tomography System Using Fan Beam Projection Technique For Stagnant Sample Visualization*. Ma te The i . Unive iti Te nolo i Mala ia 2015.

64 Ra hid W. N. A. Moha ad E. J. Rahi R. A. A e an H. L. M. A d llah J. Moha ad M. M. Ha hi H. Shai M. F. and Ma wah O. M. F. Miniat e Pa allel ECT: A P eli ina St d U in Co ol. *Jurnal Teknologi*. 2015. 77 17 : 37-41.

65 Miled M. A. and Sawan M. Dielect o ho e i -Ba ed Inte ated La -on-Chi o Nano and Mic o-Pa ticle Mani lation and Ca acitive Detection. *IEEE Transaction On Biomedical Circuit and System*. 2012. 6 2 : 120-132.

66 D n chai W. Chaila a l O. and Hen C. S. A Low-co t Si le and Ra id Fa ication Method o Pa e - a ed Mic o l idic in Wa Sc een-P intin . *The Analyst*. 2011. 136 1 : 77-82.

67 H X. and an W. Plana Ca acitive Sen o – De i n and A lication . *Sensor Review*. 2010. 30 1 : 24-39.

68 Rah an M. F. A. Mana A. A. and A had M. R. Ca acitive E ect o Co lana Elect ode Pa tiall O t ide the Mic ochannel Re ion o Unde wate Mic o l idic- a ed Sen o . *Indian Journal of Marine Sciences*. 2013. 42 8 : 987-991.

69 Chan K. S. *Real Time Image Reconstruction for Fan Beam Optical Tomography System*. Ma te The i . Unive iti Te nolo i Mala ia 2002.

70 Rahi R. A. Rahi an M. H. F. Leon L. C. Chan K. S. and Pan J. F. Ha dwa e I le entation o M lti le Fan Bea P o ection Techni e in O tical Fi e P oce To o a h . *Sensors*. 2008. 8 5 : 3406-3428.

71 Rahi R. A. Leon L. C. Chan K. S. Fa al l Rahi an M. H. and Pan J. F. Solid/Ga Concent ation Mea e ent U in M lti le Fan Bea O tical To o a h . *The Open Optics Journal*. 2008. 2 1 : 21-34.

72 I a en . A Review o Recon t ction Techni e o Ca acitance To o a h . *Measurement Science and Technology*. 1996. 7 3 : 325-337.

73 D a ow i T. Jean e e L. F. C. and Jawo i A. J. A lication o Elect ical To o a h o Ga -Solid and Li id-Solid Flow - A Review. *Powder Technology*. 2000. 112 3 : 174-194.

74 Xie C. G. G. H an S. M. M. Bec M. S. S. Ho le B. S. S. Tho n R. Lenn C. Snowden D. and Bec M. S. S. Elect ical Ca acitance

To o a h o Flow I a in : S te Model o Develo ent o I a e Recon t ction Al o ith and De i n o P i a Sen o . *IEE Proceedings G Circuits, Devices and Systems*. 1992. 139 1 : 89-98.

75 H an S. M. Pla ow i A. B. Xie C. G. and Bec M. S. To o a hic I a in o Two-Co onent in Ca acitance Sen o . *Journal of Physics E: Scientific Instrument*. 1989. 22 3 : 173-177.

76 Alla A. K. and Dea e W. A. Elect ical Ca acitance To o a h Di ital P oce in Plat o ECT-DPU . *42nd Annual Conference of the IEEE Industrial Electronics Society*. Octo e 23-26 2016. Flo ence Ital : IEEE. 2016. 4767–4771.

77 Re atn A. Chit a l K. Soi A. and W ti V. Elect ical Ca acitance To o a h S te o Monito in P oce Flow In Pi e. *SICE Annual Conference 2010*. A t 18-21 2010. Tai ei Taiwan: IEEE. 2010. 3229–3232.

78 an W. Q. and Li S. Elect ical Ca acitance To o a h with a S a e Sen o . *Electronics Letters*. 1999. 35 4 : 295-296.

79 G t . and Wolan i P. Fla e I a in in 3D Elect ical Ca acitance To o a h . *Combustion Science and Technology*. 2010. 182 11 : 1580-1585.

80 Rahi R. A. Thia C. K. P anathan J. and S ia an . S. L. E edded S te Ba ed O tical To o a h : the Concent ation P o ile. *Sensor Review*. 2009. 29 1 : 54-62.

81 M i S. . M. Rahi R. A. Rahi an M. F. H. Sahlan S. Shai M. F. P anathan J. and Moha ad E. J. O tical To o a h : A Review On Sen o A a P o ection A an e ent and I a e Recon t ction Al o ith . *International Journal of Innovative Computing*. 2011. 7 7 : 3839-3856.

82 Rahi an M. H. F. Rahi R. A. Rahi H. A. M i S. . M. and Moha ad E. J. Ult a onic To o a h – I a e Recon t ction Al o ith . *International Journal of Innovative*. 2012. 8 1 : 527-538.

83 Leon L. C. *Implementation of Multiple Fan Beam Projection Technique in Optical Fibre Process Tomography*. Ma te The i . Unive iti Te nolo i Mala ia 2005.

84 P anathan J. n F. R. A o N. M. N. Rahi R. A. Phan F. A. Rahi H. A. Leow P. L. and A a K. H. A Novel Elect ical Ca acitance

Sen o De i n o D al Modalit To o a h M lti ha e Mea e ent. *Jurnal Teknologi (Sciences and Engineering)*. 2013. 64 5 : 43-45.

85 Wan H. G. Qi G. . hao G. R. Mo X. . L Q. G. and an W. Q. Monito in Solid Flow in a Ci c latin Fl idi ed Bed with E te nal Heat E chan e Elect ical Ca acitance To o a h . *IEEE International Conference on Imaging Systems and Techniques (IST).* J 1 16-17 2012. Manche te En land: IEEE. 2012. 78–82.

86 Na A. A. Ah ed W. H. and El-Da ha hni W. W. Co lana Ca acitance Sen o o Detectin Wate Int ion in Co o ite St ct e . *Measurement Science and Technology*. 2008. 19 7 : 75702.

87 Thiele S. Silva M. J. D. and Ha el U. Ca acitance Plana A a Sen o o Fa t M lti ha e Flow I a in . *IEEE Sensors Journal*. 2009. 9 5 : 533-540.

88 Ma i hev A. V. Ra an K. S. an F. D . and ahn M. Inte di ital Sen o and T an d ce . *Proceedings of the IEEE* 2004. 92 5 : 808-844.

89 El en C. Glawdel T. Chan D. and Ren C. L. Detection o Mic od o let Si e and S eed in Ca acitive Sen o . *Sensors and Actuators A: Physical*. 2011. 171 2 : 55-62.

90 an W. Q. and o T. A. New AC- a ed Ca acitance To o a h S te . *IEE Proceedings - Science, Measurement and Technology*. 1999. 146 1 : 47-53.

91 Moha ad E. J. *A Segmented Capacitance Tomography for Visualising Material Distributions in Pipeline Conveying Crude Palm Oil*. PhD. The i . Unive iti Te nolo i Mala ia 2012.

92 H ieh J. *Computed Tomography: Principles, Design, Artıfacts, and Recent Advances*. SPIE e . 2003.

93 an W. De i n o Elect ical Ca acitance To o a h Sen o . *Measurement Science and Technology*. 2010. 21 4 : 42001.

94 Chen D. an W. and Den X. Co a i on o Th ee Elect ical Ca acitance To o a h S te . *IEEE International Conference on Imaging Systems and Techniques (IST)*. J 1 1-2 2010. The aloni i G eece: IEEE. 2010. 57–62.