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Mathematical Modeling of DC Cardiac Ablation

Sowmya Reddy Narala
Cleveland State University

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SOWMYA REDDY NARALA

Bachelor of Mechanical Engineering

Jawaharlal Nehru Technological University, India

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and the College of Graduate Studies by

_____

Thesis Committee Chairperson, Dr. Majid Rashidi

_____

Department/Date

_____

Dr. Rama S.R.Gorla

_____

Department/Date

_____

Dr. Asuquo Ebiana

_____

Department/Date

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MATHEMATICAL MODELING OF DC CARDIAC ABLATION

SOWMYA REDDY NARALA

ABSTRACT

This thesis presents a mathematical modeling of the cardiac DC ablation procedure. The model treats the procedure as a one dimensional heat transfer phenomenon taking place across the thickness of the myocardium. The model further considers a constant 37 ^{o}C for one of the boundary condition of the affected tissue, and the temperature of the other boundary condition is set to be a time dependent square-pulse variations. The parameters defining this time dependent boundary condition is used to perform parametric studies to predict tissue temperature at different depth of the myocardium. The initial condition of the myocardium prior to the ablation procedure is considered to be also constant and at 37 ^{o}C. MATLAB was used to solve the parabolic partial differential equation that describes the temperature variations within the myocardium. The duration of off-and-on square-pulse controlled temperature at the inner wall of the myocardium showed to be influential in the depth of intentional lesion within the myocardium. In case of a 1.5-seconds on-time for a 60 ^{o}C wall temperature, and a 0.5-second off-time, the time taken to have a lesion depth of 0.26 mm reaching 55 ^{o}C was about 6.32 seconds.

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NOMENCLATURE

C: Thermal Conductivity

c: Specific heat

ρ: Density

k: Thermal diffusivity

T_c: Temperature from Catheter i.e. source temperature on target tissue

L: Period in Fourier series

CHAPTER I

INTRODUCTION TO CARDIAC ABLATION

Use of the word "Cardiac" in the title suggests that the study is on heart and Ablation is a process in which required amount of material is removed from the surface of an object by vaporization, chipping or other erosive processes. Together Cardiac ablation is a process in which a small heart tissue is intentionally destroyed by minimal invasion; this is usually done by the use of electrical energy and heat. Cardiac Ablation is a procedure to cure arrhythmias, which is an irregularity in the heart rhythm. Most common type of arrhythmia is referred to an Atrial Fibrillation.

1.1   Cardiac Ablation Benefits and Complications

Like any other procedure cardiac ablation also has benefits accompanied with complications. The main benefits of cardiac ablation are the use of less invasive procedure, short treatment time, high success rates and low cost. Unlike traditional open heart surgery cardiac ablation is a minimal invasive treatment. Arrhythmia should be completely cured with this procedure, without any recurrence of the problem in the

future. The treatment time is short does not last more than an hour and has huge success rates. The cost for the treatment is very reasonable and less compared to a traditional surgery.

The primary tool of performing cardiac ablation, namely the catheter, is a foreign object when contacted with heart muscle, and in turn, it could cause irritation at the site of ablation, slight bleeding might also occur and blood pressure also changes. All these complications during cardiac ablation last only till the completion of the process.

There are some complications which can be considered major, such as hole in the heart wall during the process which leads to condition called cardiac tamponade, excess bleeding at the site, formation of blood clots, stroke due to blockage in the coronary artery and in some cases there is formation of small hole between heart and esophagus which is dangerous.

1.2   Previous works in the field

Cardiac ablation was evolved in the year 1982 which used catheter to heat sites and segments of the heart tissue responsible for irrigular electrical activities. At the beginning stage of this technology direct current were used to energize the catheter through external device. However use of DC in ablation caused excess damage to tissue because it was difficult to control such high voltage. This lead path to usage of different energies like microwave, laser, radiofrequency and cryoprobes in ablation process.

(Marcus and Hynynen)(1)in their article stated the background of cardiac ablation and apparatus used for it. This article states that as the above mentioned each of the cardiac ablation techniques have one or more disadvantages, so made an effort to introduce ultrasonic energy to destroy the tissue.

(Lai)(2) worked on estimating lesion size during RF cardiac ablation. This report concludes that the lesion depth during cardiac ablation can be 3-5mm and also states that the measurement of electrode convective coefficient plays a significant role in simulation of cardiac ablation.

According to (Wolfgang M. Hartung)(3)and (Cao)(4)the operating temperatures during ablation can vary between 50- 80℃. Damage to the tissue starts only after the temperature attains 50℃ but lesion can be formed at higher temperatures not higher than 90℃ because such high temperatures might cause excess damage to tissue than required.

1.3   Contribution of my work

Many techniques were emerged in time period to cure cardiac ablation, but Radio frequency cardiac ablation is the most prominent of all. There is necessity to improve this technique to attain high success rates by eliminating the risk. It is the purpose of this work however to re-examine DC ablation and devise a strategy for the temperature control. With proper control of the temperature at the catheter tip, lesion depth and diameter could be controlled. This work attempts to determine appropriate time

dependent temperature variations at the catheter tip so that a successful ablation is achieved.

CHAPTER II

ANATOMY OF HEART AND ITS ELECTRICAL ISSUES

Every object in nature has a cycle so as the human heart. In order to have a clear idea about the cycle and mechanism of the heart, knowledge of heart's anatomy is mandatory.

2.1   Heart Anatomy and Its Function As A Pump

Main parts in human heart are the arteries and veins, heart chambers, heart valves and conduction system. The de-oxygenated blood coming from veins goes in the upper chambers of the heart from which it is send to lungs through the pulmonary artery. The blood then gets oxygenated in lungs and is send back to lower chambers of heart through pulmonary vein. Aorta carries oxygenated blood to the whole body from the lower chamber of the heart. The conduction system in the heart is responsible for the blood flow between the chambers. Heart Anatomy can be explained as below:

Superior Vena Cava and Inferior Vena Cava: Both Superior and Inferior Vena Cava bring the de-oxygenated blood form the upper and lower parts of the body respectively into the right chamber of the heart.
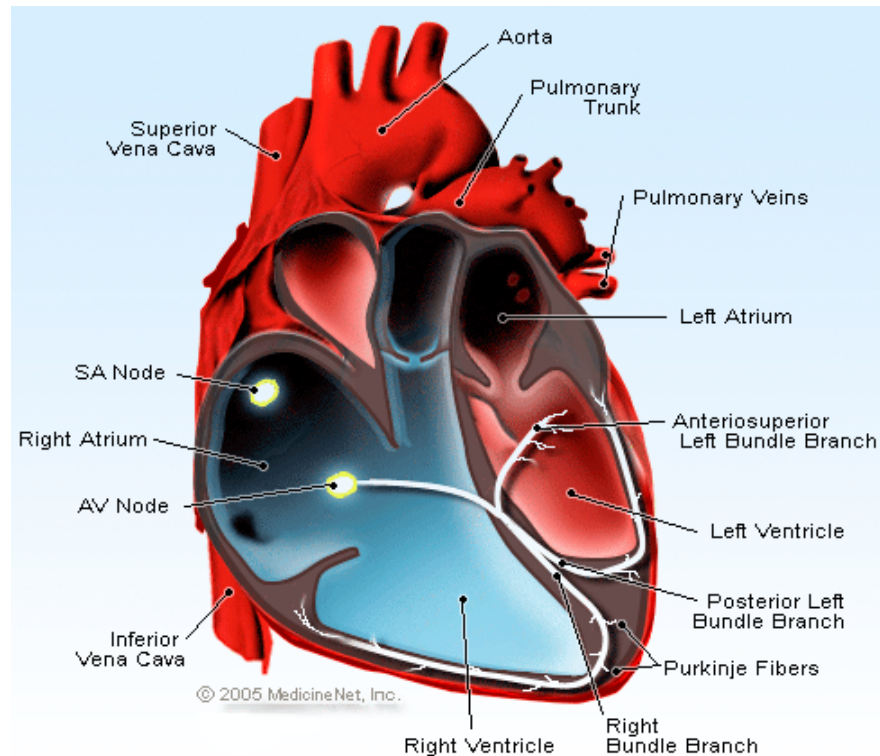
Figure 1:   Anatomy of Heart

Heart chambers: There are four chambers in heart. The two upper chambers of heart are left atrium and right atrium which together are called Atria and two lower chambers of heart are left ventricle and right ventricle which are together called as Ventricles. These chambers in heart are separated by a wall called Septum.

Heart valves: Tricuspid, Mitral, Pulmonary and Aortic are the four values in the heart. Tricuspid valve and Mitral valve acts as a separation gate between atria and ventricles in

right and left chambers of the heart respectively whereas Pulmonary value and Aortic valve acts as separation for the right ventricle and pulmonary artery. When the atria contracts mitral valve opens and allows the oxygenated blood flow from left atrium to left ventricle and tricuspid valve opens and allows de-oxygenated blood flow from right atrium to right ventricle.
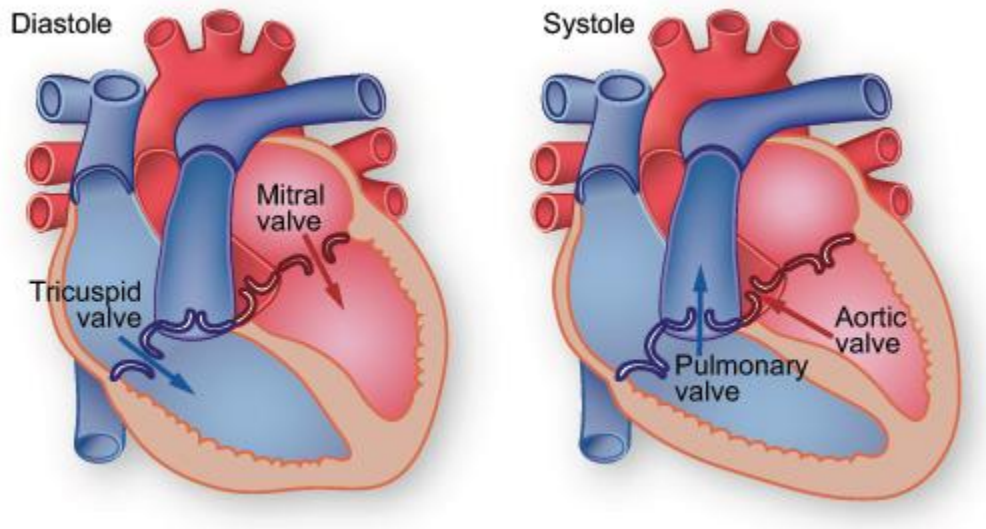
Figure 2: Diastole and Systole of Heart

When the ventricles contract both mitral and tricuspid valves closes preventing the back flow of blood from ventricles to atria, hence forcing to exit through aortic valves and pulmonary valve respectively.

Conduction system: Electric signals generated in the heart are responsible for the contraction and expansion movements of the heart muscle. Sinoatrial node located in the right atrium, Atrioventricular node located in the septum and His bundle located along the walls of the lower portion of the heart together act as the electrical system in heart.
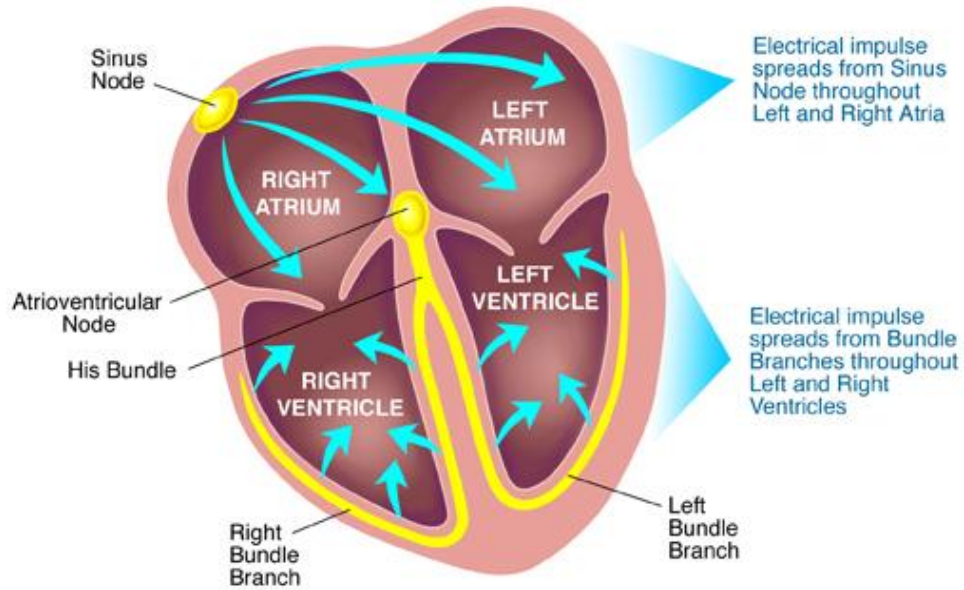
Figure 3:   Shows the pathway of electrical impulses in heart

Electrical signals generate at Sinoatrial node or SA node, which is also known as natural pacemaker. These signals reach Atriovenicular node through the walls of the heart compressing the atria to push blood into ventricles. The signals then pass through the His bundle from Atriovenicular node and contract the walls of the ventricles thus pushing blood out of the ventricles.

2.2   Typical electrical problems with human heart

A single heart beat is described as a contraction and an expansion of the heart muscle. The conduction system in heart takes main part in contraction and expansion of the heart muscle. A normal heart beats in regular intervals which in turn prove that the

conduction system is in good condition. Slight irregularity in the interval is also considered as cardiac disorder. Malfunctioning of the electrical system leads to such irregularities known as Arrhythmia. Depending on the position and pace arrhythmia is categories to four main types, they are premature (extra) beats, supraventricular arrhythmias, ventricular arrhythmias, and bradyarrhythmias. Premature beats are the most common and harmless type. Supraventricular and ventricular arrhythmias occur in atria and ventricle respectively. The condition in which heat beats less than sixty times per minute is known as bradyarrhythmia.

Atrial Fibrillation is a very familiar type of arrhythmia which can be listed under supraventricular arrhythmia. In this case electrical impulses do not travel in an organized path which causes shivering to the heart muscles, thus the name fibrillation. Atrial Fibrillation can be treated with medications, however this is not the complete cure as there are chances for the disease to recur in some cases. Treatments such as Electrical Cardioversion, AV Node Ablation and Pacemaker Implantation, Radiofrequency Catheter Ablation, Open heart surgery and Mini-Maze surgical procedure are considered effective to treat Atrial Fibrillation. Of all the procedures listed Radio frequency catheter ablation is a very minimal invasive and efficient procedure.

2.3   Cardiac Disorders Fixed With Ablation and Its Procedure

Most of the Supraventricular tachycardia arrhythmias such as Atrial Fibrillation, Atrial Flutter and Wolff-Parkinson-White syndromecanbe fixed with Ablation procedure.

As mentioned earlier cardiac ablation corrects the heart rhythm problem caused by disorganized electrical impulses which originate at the SA node of the left atrium. This procedure is recommended by doctors only if the medication cannot control the disease or if the patient experiences any side effects due to medication and in high risk cases.

Ablation Procedure: In this process a series of flexible catheters are inserted into the blood vessel through groin as shown in the below figure. With the help of X-ray the catheter can be guided through blood vessels/vein in the body to reach the area of the heart to be operated.
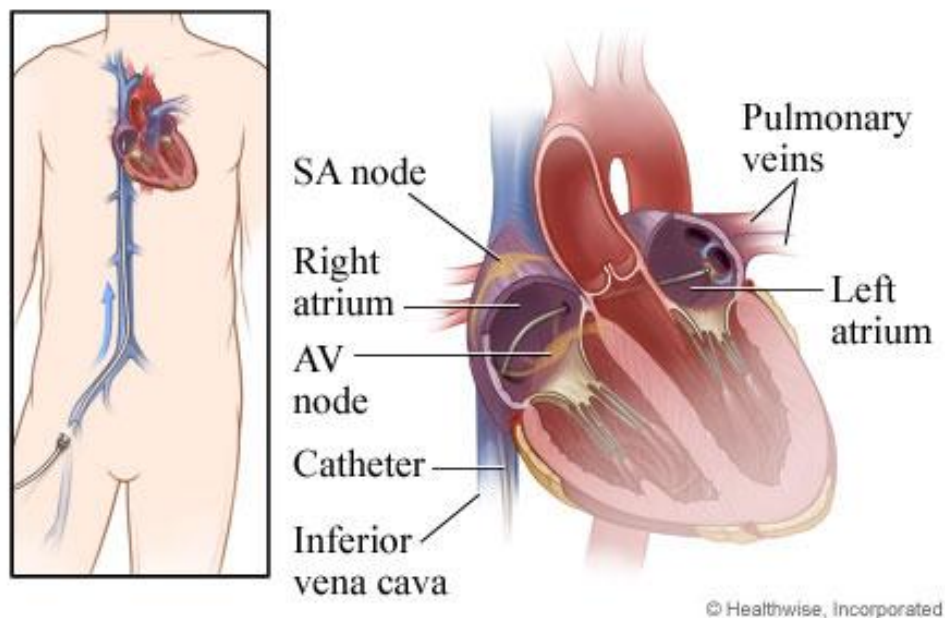
Figure 4: Catheter insertion into the body for ablation

When the catheter is placed in heart, correct location causing arrhythmia is identified by the doctors by sending the electrodes into different places in the heart. Once the location

is detected, electrical energy is induced into the catheter with the help of an external device which in turn destroys the affected area.
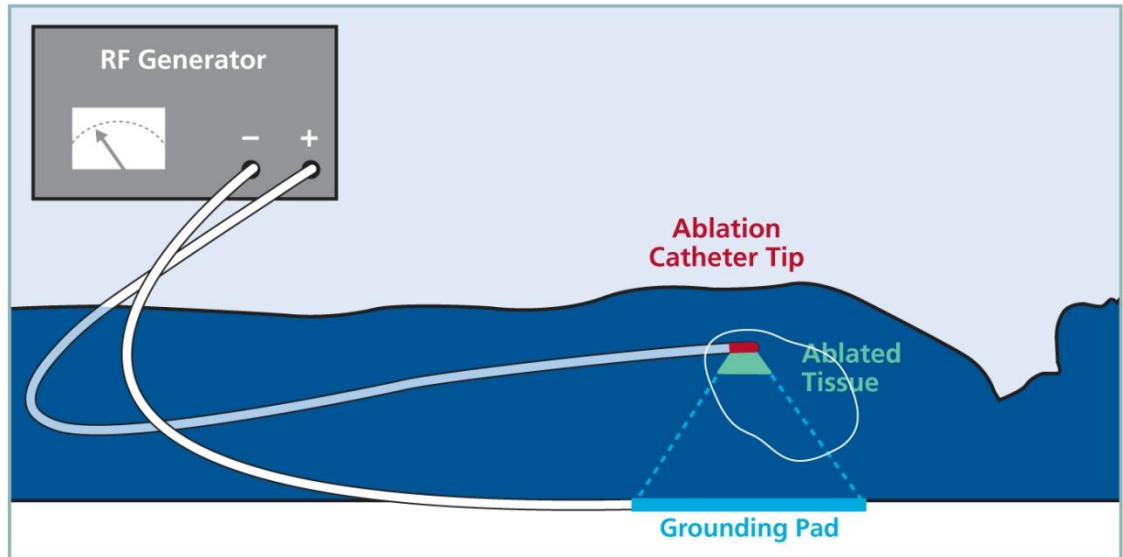
Figure 5:   Shows the equipment and the way ablation procedure is handled

This external device is used to control the temperature at the catheter tip. Earlier direct current was used to control the temperature, later microwave, laser and radiofrequency energies came into use. However studies are still going on the several factors for a successful ablation procedure. This thesis is to do such an attempt.

CHAPTER III

MATHEMATICAL MODELING

3.1   Types Of Ablation

Cardiac ablation emerged as the most typical type of treatment for Atrial Fibrillation. Main aim in any of the ablation process is to destroy the tissue which acts as an obstacle for the correct pathway of the electrical impulses, which leads to arrhythmia. In order to achieve that, the tissue is made a nonconductor either by heating or cooling it to destroy. Different types of ablations are Cardiac Cryoablation, Radiofrequency ablation and Laser ablation.

Cardiac Cryoablation: In this process extreme cold conditions are used to cure Atrial fibrillation, hence the name Cryoablation. The catheter used in this process is called cryoprobes containing hollow needles in which refrigerant, a cool fluid is circulated. The cells at the affected area are deactivated forming a lesion which no longer conducts electrical impulses.
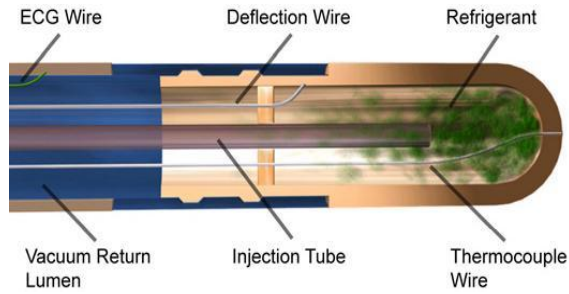
Figure 6:   Cryoprobes used in cryoablation   Figure 7:   Cryoablation procedure at
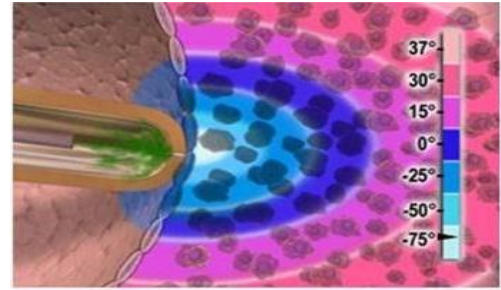
an affected area

Laser Ablation: This is one of the ablation processes in which laser with frequency ranging from 810 to 1470 nanometers (nm) is passed through the catheter and heats up the tissue to form a lesion to organize the pathway of the electrical impulses of the heart.
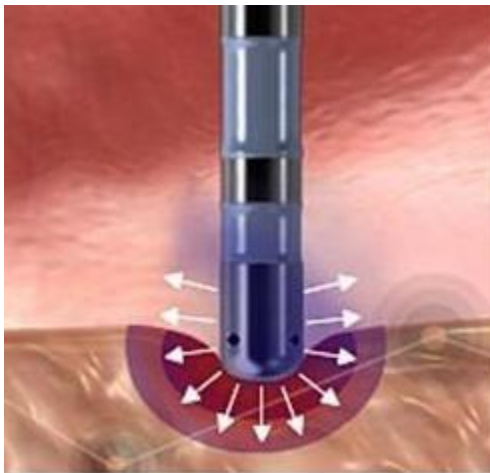
Figure 8:   Catheter located at heart tissue in Radiofrequency cardiac ablation

Radiofrequency Ablation: This procedure is similar to laser ablation except radio frequency is passed through the catheter instead of laser. The radio frequency ranges from 300 kHz to 750 kHz is used in this process.

However post cryoablation the chances of recurrence of arrhythmia are high and in laser ablation too much of burning might take place because of the intense heat energy which damages the excess area of heart muscle. Therefore of all the procedures mentioned above Radiofrequency cardiac ablation is mostly recommended and very prominent procedure.

3.2   Mathematical modeling of the ablation procedure according to the method

One dimensional heat transfer equation shown as Eq. (3.2.1) is considered for the cardiac ablation process in this thesis.

$$\frac{\partial u}{\partial t} = \frac{C}{c\rho}\frac{\partial^2 u}{\partial x^2}$$

Equation (3.2.1)

$$k = \frac{C}{c\rho}$$

Equation (3.2.2)

$$\frac{\partial u}{\partial t} = k\frac{\partial^2 u}{\partial x^2}$$

Equation (3.2.3)

Where u, x, t are temperature of the myocardium tissue, depth of the myocardium tissue and ablation time respectively. Temperature 'u' is the function of depth 'x' and time 't'. 'k' is thermal diffusivity.

Here thermal diffusivity is thermal conductivity 'C' divided by density 'ρ' and specific heat 'c'. Its value can be obtained by considering the thermal properties of heart tissue, we assume thermal conductivity as $0.531\ W/mK$, Specific heat as $3111\ J/(kg\ K)$ and density as $1100\ kg/m^3$ from different sources.

Value of 'k' is obtained below by substituting all the thermal properties in equation

3.2.2

$$k = \frac{0.531\ \frac{W}{mK}}{1100\ \frac{kg}{m^3} * 3111\ \frac{J}{kgK}} = 1.5516 * 10^{-7}\ \frac{m^2}{sec}$$

$$k = 1.5516 * 10^{-1}\ \frac{mm^2}{sec}$$

Equation (3.2.3) can be written as

$$\frac{\partial u}{\partial t} = 0.15516\ \frac{\partial^2 u}{\partial x^2}$$

Equation (3.2.4)

Below figure explains the initial and boundary condition of the tissue
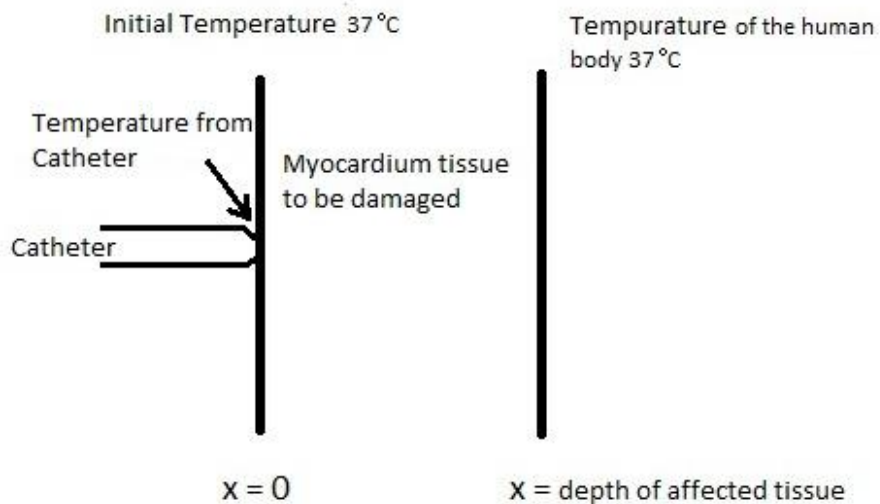
Figure 9:   Shows the schematic diagram of tissue conditions

Initial Condition:

Initially the temperature is temperature of the human body, 37 °C. At this initial point the catheter comes in contact with the tissue to induce the heat energy to destroy the cells which in turn makes the tissue inactive for any further electric conduction. As mentioned earlier u is the function of depth x and time t, therefore initial condition is can be denoted as

$$u(x,0) = 37 \text{ °C}$$

Boundary Condition:

In this thesis several results were noted by varying the left boundary condition, i.e. by inducing different temperatures into the tissue with the help of catheter. The temperature at the right boundary condition should be maintained at 37 °C which is the body temperature. Temperature at the left boundary condition is assumed to be a Fourier series equation in order to have regular intervals of temperature changes to avoid over heating of tissue with constant temperature.

Right boundary condition, $u(x, t) = 37$ °C. 'x' is the tissue depth.

Left boundary equation is the Fourier series equation shown below.

$$u(0, t) = a_0 + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi t}{L} + b_n \sin \frac{n\pi t}{L} \qquad \text{Equation (3.2.5)}$$

Case 1:

$u(t) = 0 \qquad$ -L < t < 0

$u(t) = T_c \qquad$ 0 < t < L $\qquad T_c$ is the temperature from catheter

Figure 10: Pictorial representation of Case 1

$$a_0 = \frac{1}{2L} \int_c^{c+2L} u(t)\,dt; \quad a_n = \frac{1}{L} \int_c^{c+2L} u(t) \cos\frac{n\pi t}{L}\,dt; \quad b_n = \frac{1}{L} \int_c^{c+2L} u(t) \sin\frac{n\pi t}{L}\,dt$$

Interval c to c+2L is taken as –L to L, so c is –L.

Solving above equations considering Case 1 results in $a_0 = \frac{T_c}{2}$; $a_n = T_c$ for n=0

$$b_n = \frac{T_c}{n\pi}(1 - \cos n\pi)$$

Substituting values a_0, a_n and b_n in equation (3.2.5), left boundary condition can be shown as

$$u(0,t) = \frac{T_c}{2} + \frac{T_c}{\pi} \sum_{n=1}^{\infty} \frac{1}{n}(1 - \cos n\pi) \sin\frac{n\pi t}{L} \qquad \text{Equation (3.2.6)}$$

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Case 2:

$u(t) = T_c$ $\qquad$ $0 < t < \frac{3}{2}L$ $\qquad$ T_c is the temperature from catheter

$u(t) = 0$ $\qquad$ $\frac{3}{2}L < t < 2L$

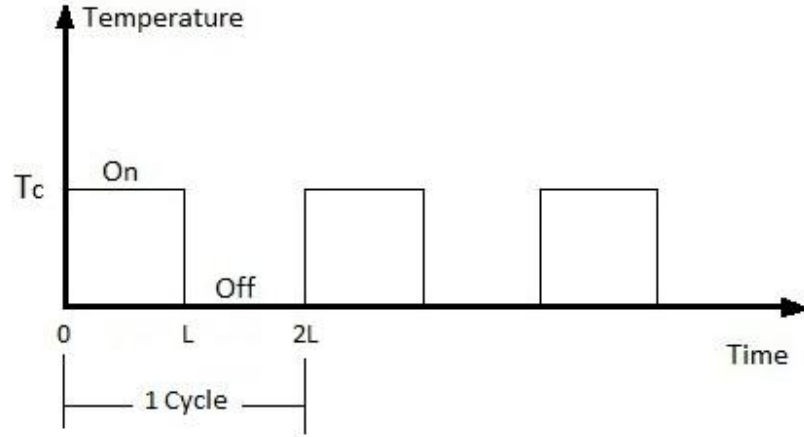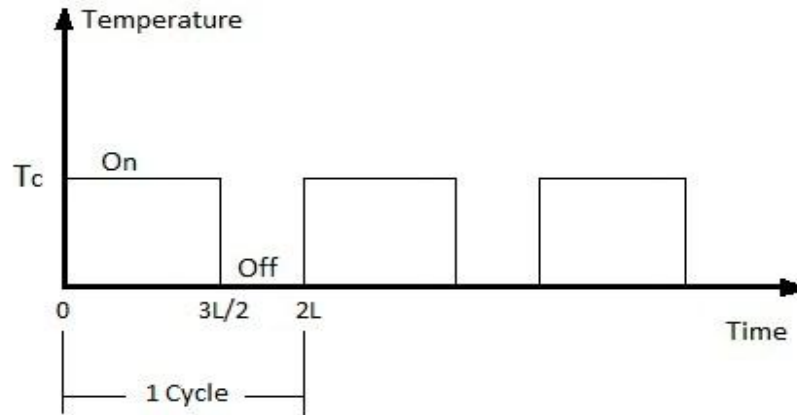Figure 11: Pictorial representation of Case 2

$$a_0 = \frac{1}{2L} \int_c^{c+2L} u\,t\,dt; \; a_n = \frac{1}{L}\int_c^{c+2L} u\,t\,\cos\frac{n\pi t}{L}dt \;; b_n = \frac{1}{L}\int_c^{c+2L} u\,t\,\sin\frac{n\pi t}{L}dt$$

$$a_0 = \frac{3T_c}{4};$$

$$a_n = \frac{T_c}{n\pi}\sin\frac{3n\pi}{2}$$

$$b_n = \frac{T_c}{n\pi}\left(1 - \cos\frac{3n\pi}{2}\right)$$

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Substituting values a_0, a_n and b_n in equation (3.2.5), left boundary condition can be shown as

$$u\ (0, t)\ = \frac{3T_c}{4} + \frac{T_c}{\pi} \sum_{n=1}^{\infty} \frac{1}{n}\ \sin(n\pi(\frac{3}{2} - \frac{t}{L})) + \sin\frac{n\pi t}{L} \qquad \text{Equation (3.2.7)}$$

MATLAB functions used: MATLAB Partial differential equation solver is used to solve the above mathematical model. The conditions which become input to the PDE solver for heat equation (3.2.4) are listed below

One Dimensional Heat Equation: $\quad \frac{\partial u}{\partial t} = 0.15516 \frac{\partial^2 u}{\partial x^2}$

Case 1:

Initial and Boundary Conditions: $\quad u(x, 0) = 37\ ^\circ C$

$$u(x, t) = 37\ ^\circ C$$

$$u\ (0, t)\ = \frac{T_c}{2} + \frac{T_c}{\pi} \sum_{n=1}^{\infty} \frac{1}{n}(1 - \cos n\pi) \sin\frac{n\pi t}{L}$$

Case2:

Initial and Boundary Conditions: $\quad u(x, 0) = 37\ ^\circ C$

$$u(x, t) = 37\ ^\circ C$$

$$u\ (0, t)\ = \frac{3T_c}{4} + \frac{T_c}{\pi} \sum_{n=1}^{\infty} \frac{1}{n}\ \sin(n\pi(\frac{3}{2} - \frac{t}{L})) + \sin\frac{n\pi t}{L}$$

'pdepe' solves systems of parabolic and elliptic PDEs in one spatial variable x and time t, of the form

$$c\left(x,t,u,\frac{\partial u}{\partial x}\right)\frac{\partial u}{\partial t} = x^{-m}\frac{\partial}{\partial x}\left(x^m f\left(x,t,u,\frac{\partial u}{\partial x}\right)\right) + s\left(x,t,u,\frac{\partial u}{\partial x}\right).$$

Equation (3.2.7)

The PDEs hold for t0 ≤ t ≤ tf and a ≤ x ≤ b. The interval [a, b] must be finite. m can be 0, 1, or 2, corresponding to slab, cylindrical, or spherical symmetry, respectively. If m> 0, then a ≥ 0 must also hold.

In above equation, f(x,t,u,∂u/∂x) is a flux term and s(x,t,u,∂u/∂x) is a source term. The flux term must depend on ∂u/∂x. The coupling of the partial derivatives with respect to time is restricted to multiplication by a diagonal matrix c(x,t,u,∂u/∂x). The diagonal elements of this matrix are either identically zero or positive.

At the initial time t = t0, for all x the solution components satisfy initial conditions of the form

$$u(x,t_0) = u_0(x).$$

At the boundary x = a or x = b, for all t the solution components satisfy a boundary condition of the form

$$p(x,t,u) + q(x,t)f\left(x,t,u,\frac{\partial u}{\partial x}\right) = 0.$$

q(x,t) is a diagonal matrix with elements that are either identically zero or never zero. Note that the boundary conditions are expressed in terms of the f rather than partial derivative of u with respect to x ∂u/∂x. Also, of the two coefficients, only p can depend on u.

The basic syntax of the solver is:

sol = pdepe(m,pdefun,icfun,bcfun,xmesh,tspan)

The input arguments can be explained below

'm' Denotes symmetry of the given problem. Is value is taken as '0' for slab, '1' for cylindrical and '2' for spherical.

'pdefun' Function defines the components of PDE. Terms c, f, s from Equation (3.2.7) are declared in this function. It has the form [c,f,s] = pdefun(x,t,u,dudx)

'icfun' Function evaluates the initial conditions. It has the form u = icfun(x)

'bcfun' Function evaluates boundary conditions. It has the form

[pl,ql,pr,qr] = bcfun(xl,ul,xr,ur,t)

'xmesh' It's a vector specifying the points at which numerical solution is requested for every value in tspan.

'tspan' It's a vector specifying the points at which a solution is requested for every value in xmesh.

CHAPTER IV

PARAMETRIC STUDY & RESULT

By assuming the lesion formation depth as 3 – 5mm and ablation time as 60 sec, a MATLAB code is built to get a solution for u i.e. temperature at different depths and times. The generated code was run by taking catheter temperature T_c as 55 ^{o}C and period as 2. The generated three dimensional graphs (Tissue temperature on Y- Axis; Time of ablation on X- Axis; Tissue depth on Z- Axis) and solution set (as in Table II in Appendix) are recorded. The code is run same way by varying catheter temperature T_c from 60 ^{o}C to 80 ^{o}C and taking the period as 2. This procedure is repeated by changing the period to 3 and recording the graphs and solution sets for all the catheter temperatures 55 ^{o}C to 80 ^{o}C. The 3D and 2D graphs are listed below.

Numerical solution computed with 20 mesh points. Period(L) as 2, and Catheter temperature(Tc) as 55
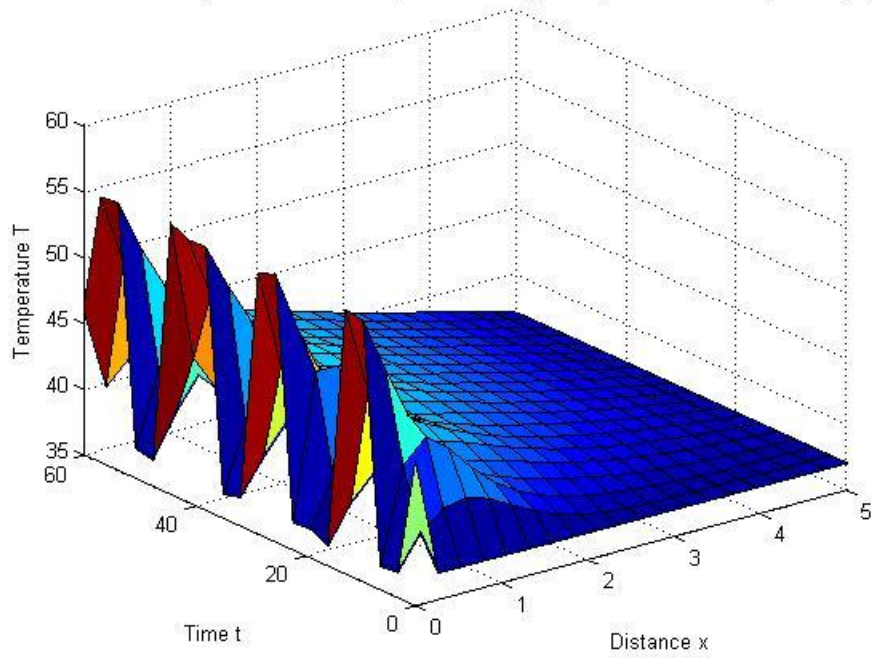
Figure 12: 3D representation of Case 1 solution set when T_c is 55 ^{o}C and period 2

Numerical solution computed with 20 mesh points. Period(L) as 2, and Catheter temperature(Tc) as 55

X: 1.053
Y: 9.474
Z: 42.06

Figure 13: 2D representation of Case 1 solution set when T_c is 55 ^{o}C and period 2

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Figure 14: 3D representation of Case 1 solution set when T_c is 60 ^{o}C and period 2
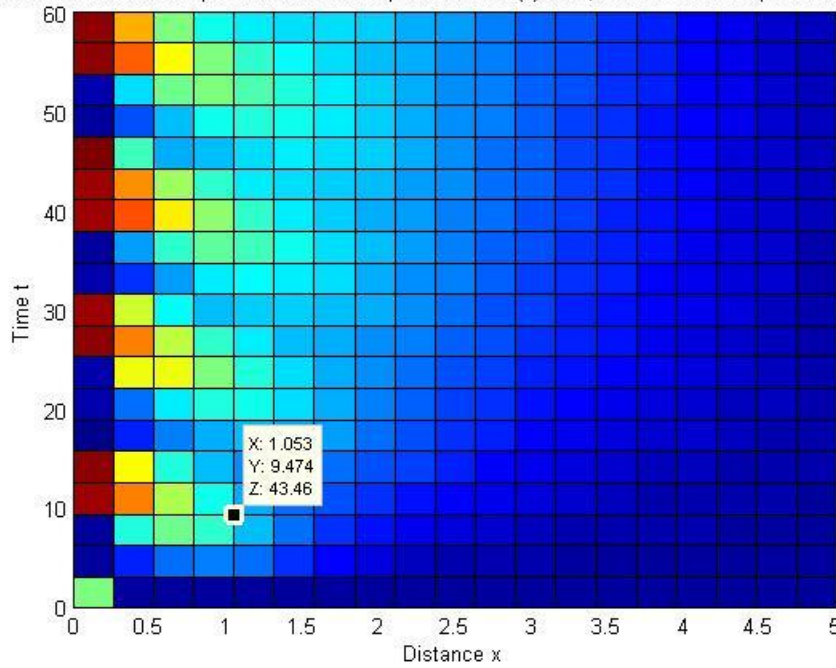
Figure 15: 2D representation of Case 1 solution set when T_c is 60 ^{o}C and period 2

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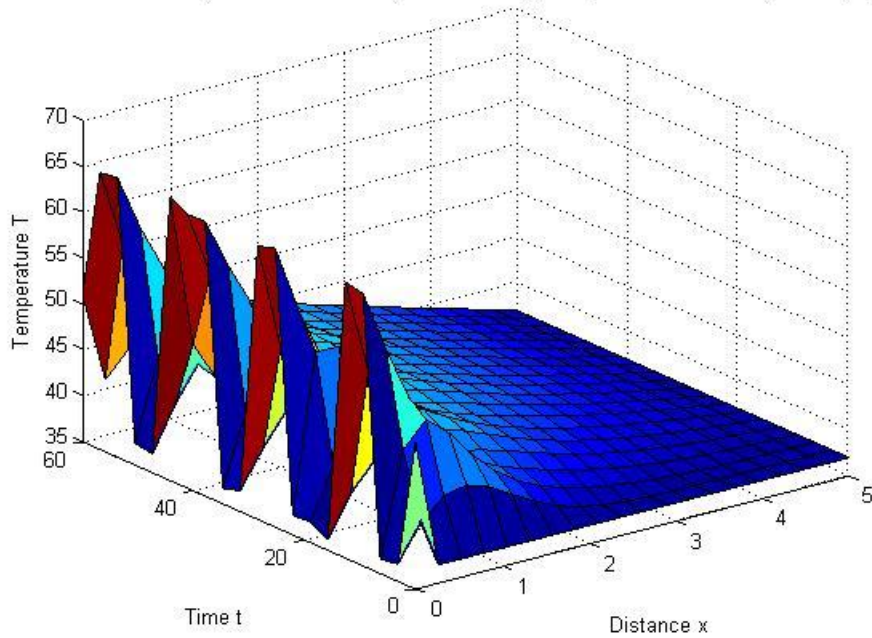
Figure 16: 3D representation of Case 1 solution set when T_c is 65 ^{o}C and period 2

Figure 17: 2D representation of Case 1 solution set when T_c is 65 ^{o}C and period 2

Numerical solution computed with 20 mesh points. Period(L) as 2, and Catheter temperature(Tc) as 70

Figure 18: 3D representation of Case 1 solution set when T_c is 70 $^{\circ}$C and period 2

Numerical solution computed with 20 mesh points. Period(L) as 2, and Catheter temperature(Tc) as 70
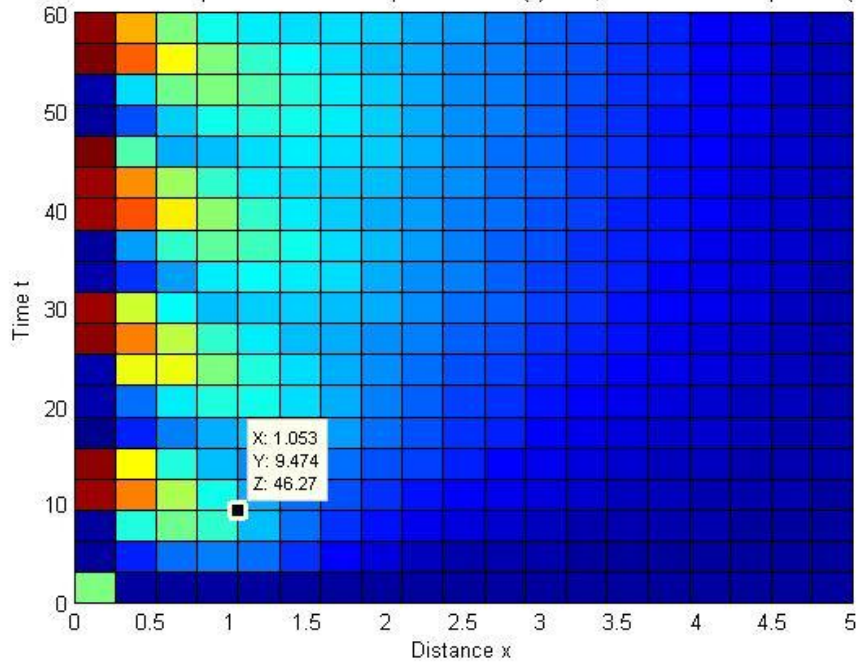
Figure 19: 2D representation of Case 1 solution set when T_c is 70 $^{\circ}$C and period 2

Numerical solution computed with 20 mesh points. Period(L) as 2, and Catheter temperature(Tc) as 75
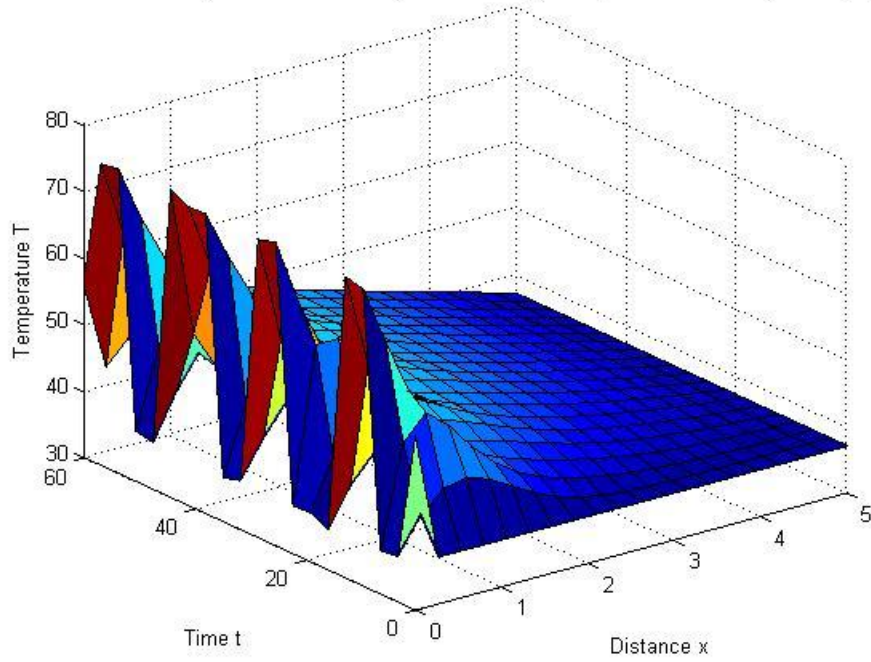
Figure 20: 3D representation of Case 1 solution set when T_c is 75 ^{o}C and period 2

Numerical solution computed with 20 mesh points. Period(L) as 2, and Catheter temperature(Tc) as 75

X: 1.053
Y: 9.474
Z: 47.68
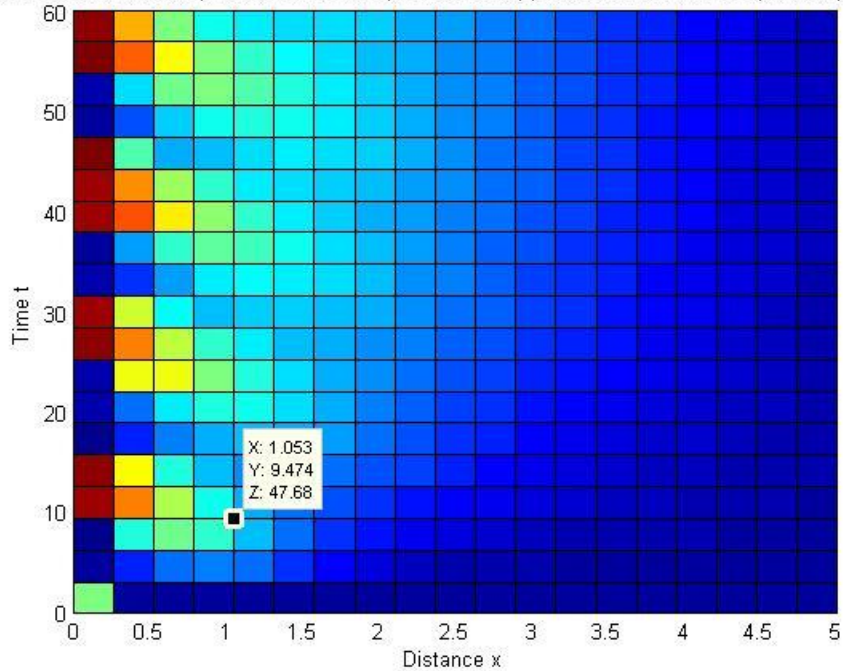
Figure 21: 2D representation of Case 1 solution set when T_c is 75 ^{o}C and period 2
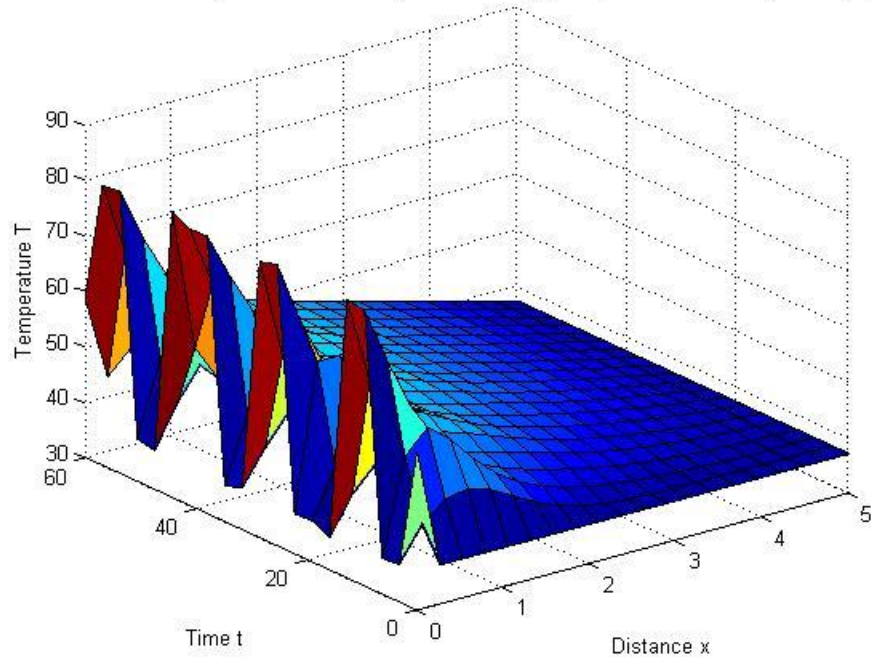
Figure 22: 3D representation of Case 1 solution set when T_c is 80 ^{o}C and period 2
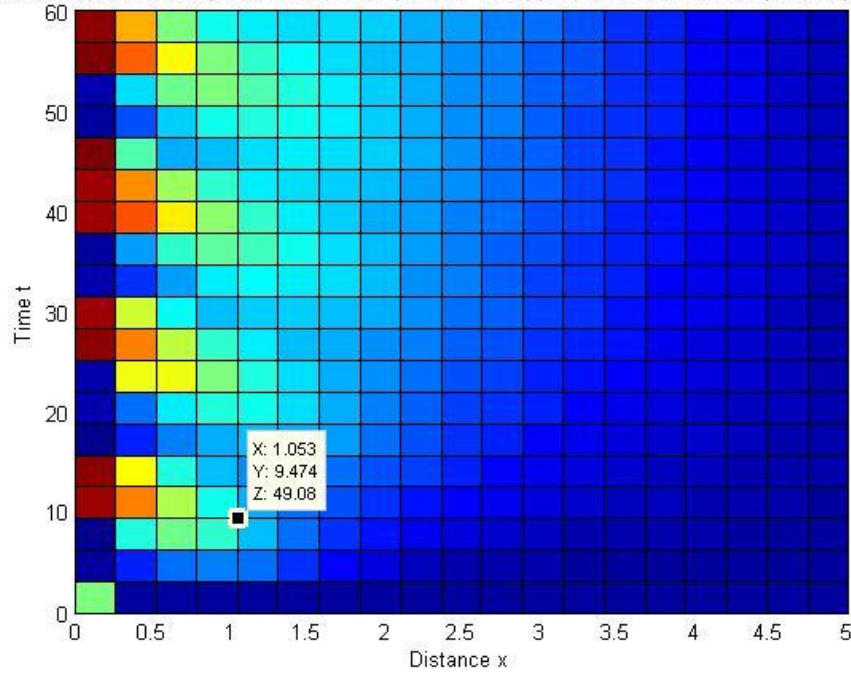
Figure 23: 2D representation of Case 1 solution set when T_c is 80 ^{o}C and period 2

Same as period 2 solution set for period 3 is also recorded. Damage of tissue starts only after the temperature crosses 50 ℃ and should not be heated above 100 ℃ which cause damage to other tissues. The time taken to attain temperature of 50 ℃ at different depths of tissue for given temperatures of catheter T_c and period as 2 and 3 is listed in the table below.

TABLE I: LISTS THE TIME TAKEN AT DIFFERENT TEMPERATURE FOR PERIODS 2 AND 3

	Period as 2 Sec						Period as 3 Sec					
	Time taken to attain 50 ℃ when Tc is						Time taken to attain 50 ℃ when Tc is					
Depth x	55	60	65	70	75	80	55	60	65	70	75	80
0.26	9.47	7.89	7.1	6.51	5.92	5.53	25.26	12.2	2.8	2.37	2.17	1.88
0.79			22.11	6.23	5.53	4.74			37.9	3.16	2.76	2.37
1.32				47.37	31.58	17.37				56.84	15.79	15
1.84					60	47.37						34.74

All the values listed here are based on the MATLAB program Case 1 in Appendix. MATLAB program Case 1 uses Fourier series with equal interval where as MATLAB program Case 2 uses Fourier series with varying intervals. Interval uses in Case 1 are –L to 0 and 0 to L and in Case 2 are 0 to 3/2L and 3/2L to 2L.

Below listed two graphs are the combinations of all the results acquired from Case1 when different Catheter tip temperatures and periods are used.
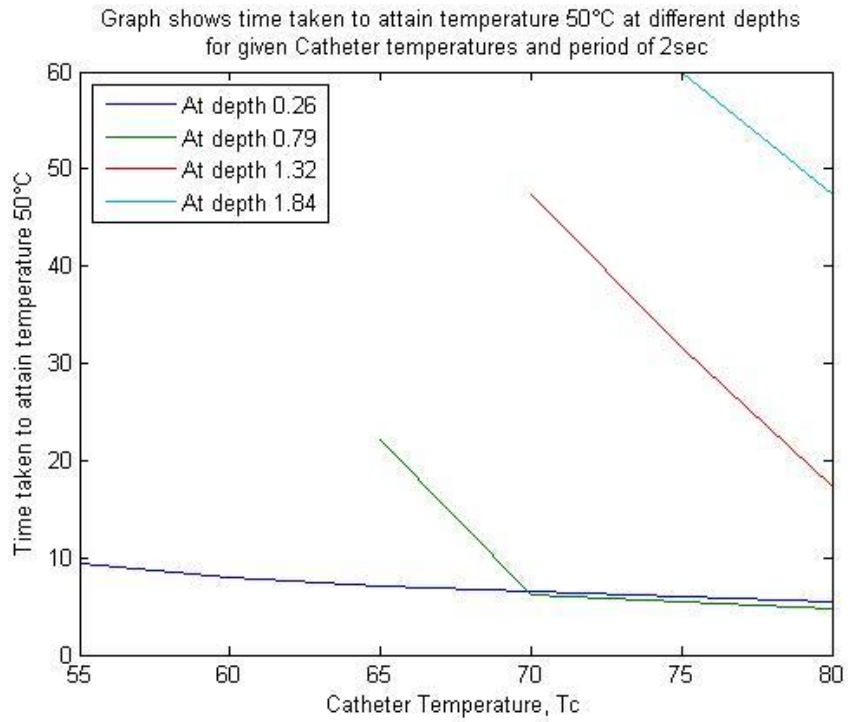
Figure 24: Temperature Vs Time graph for period as 2
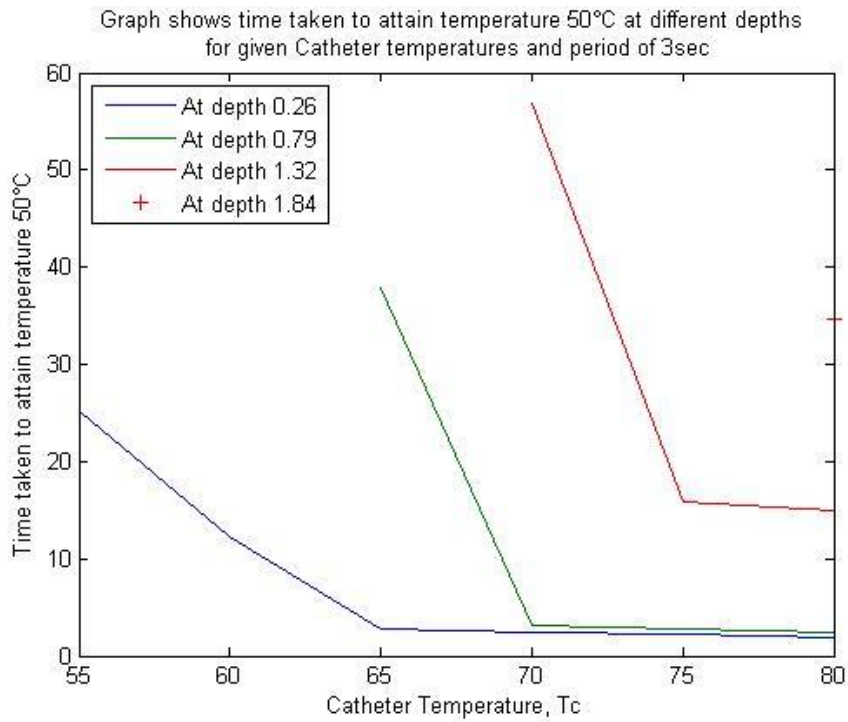
Figure 25: Temperature Vs Time graph for period as 3

However Case 2 is determined to compare the temperature values with that of Case 1. Assuming Catheter tip temperature as 60°C and period as 2, results are tabulated for Cases 1 and 2 in the Appendix Tables II and III.
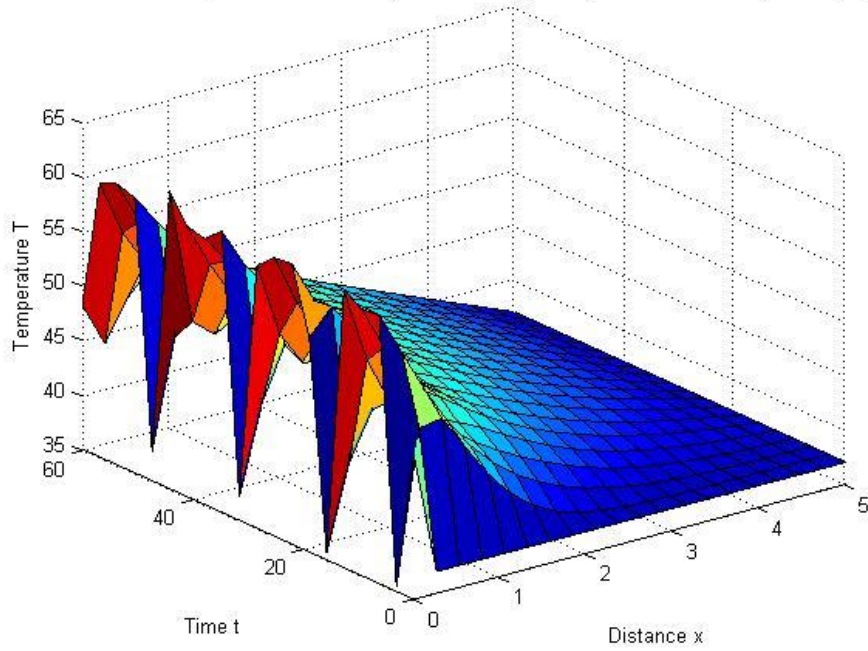
Figure 26: 3D representation of Case 2 solution set when T_c is 60 °C and period 2
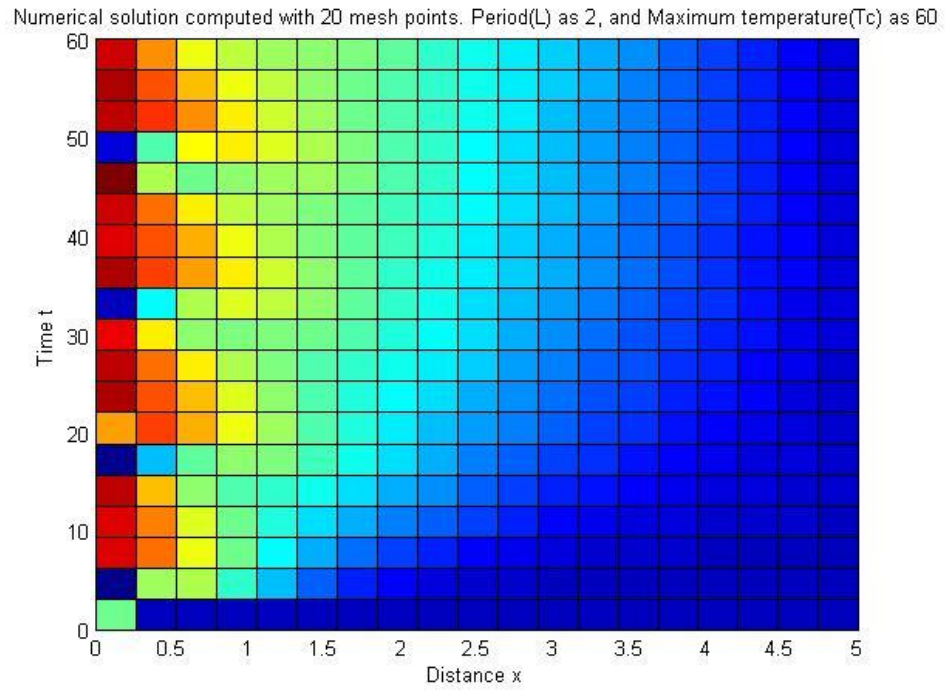
Figure 27: 2D representation of Case 2 solution set when T_c is 60 ^{o}C and period 2

CHAPTER V

DISCUSSION OF RESULTS & FUTURE WORK

Main purpose of this thesis is to improvise the DC cardiac ablation process which is most prominent method to cure the Atrial Fibrillation one of the arrhythmias. As one of such attempts one dimensional heat equation is considered and is solved in MATLAB by assuming initial condition and set of boundary conditions. This effort is made to know which temperature is effective to attain the goal of forming a lesion of 3-5 mm in reasonable time period.

After running several test cases by varying the temperatures applied to the tissue it is noticed that temperature of more than 50 ℃ is never attained after certain depth of 1.8mm. To improve the efficiency Case 2 in MATLAB program is determined which when compared with Case 1 it is noticed that the temperature is increased at a certain tissue depth as shown in Figure 28. But it is noticed that the temperature that is required to disable tissue is not attained at the required depth even in Case 2. Therefore different boundary conditions can be considered in future study.
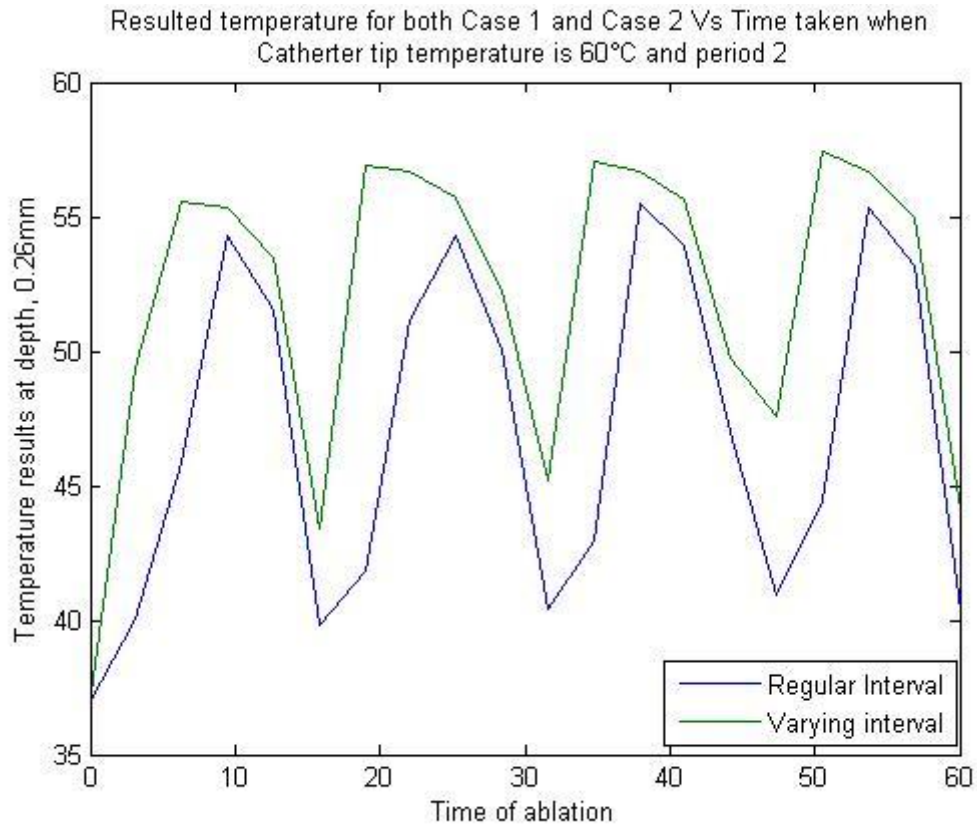
Figure 28: Graph to compare results set of regular and varying interval Fourier series

when Tc is 60℃ and period is 2.

5.1   About the Future Research Chapter

Future research is required by changing the boundary condition and temperature function used for it. There is also further possibility to work on two dimensional and three dimensional analysis. These considerations help the DC cardiac ablation to be more effective and risk free up to some extent.

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APPENDIX A - MATLAB CODE FOR CASE 1 REGULAR FOURIER SERIES; SOLUTION SET FOR T_C AS 60 AND PERIOD AS 2

MATLAB Code: Case 1 Regular Fourier Series

<u>File name: pdesolve1.m</u>

```matlab
x=linspace(0,5,20);
t=linspace(0,60,20);
m=0;
global Tmax L;
Tmax=input('Enter the value for max temperature ');
L=input('Enter the period value ');
sol=pdepe(m,@pdex1pde,@pdexlic,@pdexlbc,x,t);
u=sol(:,:,1);
surf(x,t,u);
s=horzcat('Numerical solution computed with 20 mesh points. Period(L)
as ',num2str(L),', and Maximum temperature(Tmax) as ',num2str(Tmax));
title(s);
xlabel('Distance x');
ylabel('Time t');
zlabel('Temperature T');
```

<u>File name: pdex1pde.m</u>

```matlab
function [c,f,s]= pdex1pde(x,t,u,dudx)
c=1/0.15516;
f=dudx;
s=0;
```

<u>File name: pdexlbc.m</u>

```matlab
function [pl,ql,pr,qr]= pdexlbc(xl,ul,xr,ur,t)
global Tmax L Tdiff;
Tdiff= Tmax-37;
variable=0;
for n = 1:30
variable=variable+(1-cos(n*pi))*(sin(n*pi*t/L))/n;
end
pl=ul-37-(Tdiff*.5)-(variable*Tdiff/pi);
ql=0;
pr=ur - 37;
qr=0;
```

<u>File name: pdexlic.m</u>

```matlab
function u0= pdexlic(x)
u0=37
```

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TABLE II: Resulted Temperature Solution set for Case 1 when catheter temperature is 60 $^\circ$C and period 2

x t	0.00	0.26	0.53	0.79	1.05	1.32	1.58	1.84	2.11	2.37	2.63	2.89	3.16	3.42	3.68	3.95	4.21	4.47	4.74	5.00
					Temperature attained at different depths and time taken when regular Fourier series is applied at the boundary condition Tc as 60℃, Period as 2															
0.00	48.50	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00
3.16	36.90	40.01	41.94	42.37	41.67	40.49	39.31	38.40	37.78	37.41	37.20	37.09	37.04	37.02	37.01	37.00	37.00	37.00	37.00	37.00
6.32	36.72	45.87	48.05	46.34	43.91	41.91	40.48	39.49	38.79	38.28	37.91	37.62	37.42	37.27	37.17	37.10	37.06	37.03	37.01	37.00
9.47	59.69	54.26	49.39	45.81	43.46	42.01	41.06	40.33	39.71	39.16	38.68	38.26	37.93	37.67	37.47	37.32	37.21	37.13	37.06	37.00
12.63	60.03	51.53	46.01	43.57	42.73	42.32	41.85	41.24	40.57	39.92	39.34	38.84	38.43	38.09	37.82	37.60	37.41	37.26	37.12	37.00
15.79	36.33	39.85	42.10	43.44	43.84	43.54	42.85	42.02	41.20	40.48	39.86	39.33	38.88	38.49	38.16	37.87	37.62	37.40	37.19	37.00
18.95	37.19	41.80	44.95	46.02	45.61	44.54	43.40	42.39	41.56	40.87	40.27	39.75	39.28	38.85	38.47	38.12	37.81	37.53	37.26	37.00
22.11	37.10	51.14	51.13	48.37	46.05	44.43	43.31	42.49	41.82	41.22	40.66	40.12	39.62	39.16	38.73	38.34	37.98	37.64	37.32	37.00
25.26	60.25	54.31	49.69	46.59	44.82	43.87	43.26	42.73	42.18	41.59	41.01	40.44	39.91	39.41	38.95	38.53	38.12	37.74	37.37	37.00
28.42	59.74	50.06	45.12	43.93	43.98	44.00	43.72	43.20	42.56	41.91	41.27	40.68	40.13	39.62	39.14	38.68	38.24	37.82	37.41	37.00
31.58	37.24	40.43	43.15	44.74	45.25	44.99	44.34	43.55	42.79	42.09	41.45	40.87	40.32	39.79	39.29	38.81	38.34	37.89	37.44	37.00
34.74	36.74	42.94	46.52	47.42	46.74	45.58	44.47	43.57	42.83	42.19	41.59	41.03	40.48	39.94	39.42	38.92	38.43	37.94	37.47	37.00
37.89	59.89	55.45	51.57	48.53	46.41	45.03	44.13	43.47	42.89	42.33	41.76	41.19	40.62	40.07	39.53	39.01	38.49	37.99	37.49	37.00
41.05	59.84	53.90	49.19	46.38	45.02	44.42	44.03	43.60	43.09	42.52	41.92	41.32	40.73	40.17	39.61	39.08	38.55	38.03	37.51	37.00
44.21	60.71	46.98	43.51	43.90	44.57	44.75	44.48	43.95	43.31	42.65	42.01	41.40	40.81	40.24	39.68	39.14	38.60	38.06	37.53	37.00
47.37	37.00	40.94	43.94	45.59	46.01	45.63	44.91	44.11	43.36	42.68	42.05	41.46	40.88	40.31	39.75	39.19	38.64	38.09	37.54	37.00
50.53	37.31	44.43	48.11	48.39	47.22	45.88	44.80	43.96	43.29	42.68	42.10	41.52	40.95	40.37	39.80	39.23	38.67	38.11	37.55	37.00
53.68	60.32	55.32	51.27	48.27	46.31	45.13	44.39	43.83	43.30	42.76	42.19	41.60	41.01	40.42	39.84	39.26	38.69	38.13	37.56	37.00
56.84	60.09	53.17	48.31	45.83	44.91	44.61	44.36	43.98	43.46	42.88	42.27	41.65	41.05	40.45	39.87	39.29	38.71	38.14	37.57	37.00
60.00	48.50	40.36	42.52	44.22	45.05	45.18	44.84	44.26	43.60	42.93	42.29	41.67	41.07	40.48	39.89	39.31	38.73	38.15	37.58	37.00

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APPENDIX B - MATLAB CODE FOR CASE 1 VARYING FOURIER

SERIES; SOLUTION SET FOR T_C AS 60 AND PERIOD AS 2

MATLAB Code: Case 2 Varying Fourier Series

File name: pdesolve1.m

```
x=linspace(0,5,20);
t=linspace(0,60,20);
m=0;
globalTmax L;
Tmax=input('Enter the value for max temperature ');
L=input('Enter the period value ');
sol=pdepe(m,@pdex1pde,@pdexlic,@pdexlbc,x,t);
u=sol(:,:,1);
surf(x,t,u);
s=horzcat('Numerical solution computed with 20 mesh points. Period(L)
as ',num2str(L),', and Maximum temperature(Tmax) as ',num2str(Tmax));
title(s);
xlabel('Distance x');
ylabel('Time t');
zlabel('Temperature T');
```

File name: pdex1pde.m

```
function [c,f,s]= pdex1pde(x,t,u,dudx)
c=1/0.15516;
f=dudx;
s=0;
```

File name: pdexlbc.m

```
function [pl,ql,pr,qr]= pdexlbc(xl,ul,xr,ur,t)
globalTc L Tdiff;
Tdiff= Tc-37;
variable=0;
for n = 1:10
variable=variable+(sin((3*n*pi/2)-(n*pi*t/L))+ sin(n*pi*t/L))/n;
end
pl=ul-37-(Tdiff*3/4)-(variable*Tdiff/pi);
ql=0;
pr=ur - 37;
qr=0;
```

File name: pdexlic.m

```
function u0= pdexlic(x)
u0=37
```

x \ t	0.00	0.26	0.53	0.79	1.05	1.32	1.58	1.84	2.11	2.37	2.63	2.89	3.16	3.42	3.68	3.95	4.21	4.47	4.74	5.00
		Temperature attained at different depths and time taken when varying Fourier series is applied at the boundary condition Tc as 60℃, Period as 2																		
0.00	48.14	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00	37.00
3.16	35.47	49.37	49.72	46.62	43.58	41.22	39.56	38.47	37.80	37.41	37.20	37.10	37.04	37.02	37.01	37.00	37.00	37.00	37.00	37.00
6.32	59.54	55.54	51.63	48.20	45.43	43.29	41.67	40.43	39.48	38.76	38.21	37.81	37.52	37.33	37.20	37.12	37.06	37.03	37.01	37.00
9.47	59.38	55.34	51.32	48.24	46.03	44.42	43.12	41.99	40.98	40.09	39.35	38.74	38.26	37.90	37.62	37.42	37.27	37.16	37.08	37.00
12.63	60.38	53.44	49.13	47.28	46.40	45.54	44.49	43.33	42.20	41.19	40.33	39.61	39.02	38.53	38.14	37.83	37.57	37.35	37.17	37.00
15.79	35.60	43.41	47.60	48.95	48.43	47.10	45.62	44.25	43.05	42.02	41.14	40.37	39.72	39.15	38.66	38.24	37.88	37.56	37.27	37.00
18.95	54.62	56.89	54.11	51.52	49.34	47.53	46.03	44.77	43.67	42.70	41.83	41.04	40.33	39.70	39.13	38.63	38.17	37.76	37.37	37.00
22.11	60.64	56.70	53.56	51.03	49.06	47.53	46.29	45.22	44.24	43.31	42.43	41.61	40.86	40.17	39.54	38.96	38.43	37.94	37.46	37.00
25.26	60.45	55.73	52.34	50.02	48.57	47.56	46.66	45.75	44.79	43.85	42.93	42.08	41.29	40.56	39.88	39.25	38.65	38.08	37.54	37.00
28.42	59.01	52.25	49.05	48.57	48.60	48.19	47.35	46.31	45.26	44.25	43.32	42.45	41.64	40.88	40.16	39.49	38.84	38.21	37.60	37.00
31.58	37.12	45.19	49.96	51.14	50.42	49.11	47.78	46.58	45.50	44.52	43.61	42.75	41.94	41.16	40.41	39.69	38.99	38.32	37.65	37.00
34.74	60.70	57.06	54.60	52.37	50.50	48.98	47.73	46.66	45.69	44.77	43.88	43.02	42.19	41.39	40.61	39.85	39.12	38.40	37.70	37.00
37.89	59.31	56.70	53.89	51.61	49.93	48.69	47.70	46.80	45.91	45.02	44.13	43.26	42.40	41.57	40.77	39.99	39.22	38.47	37.74	37.00
41.05	59.72	55.66	52.25	50.28	49.26	48.58	47.89	47.09	46.19	45.26	44.33	43.43	42.56	41.72	40.90	40.10	39.31	38.53	37.77	37.00
44.21	62.16	49.72	47.98	49.12	49.65	49.28	48.42	47.40	46.37	45.39	44.46	43.56	42.69	41.85	41.01	40.19	39.38	38.58	37.79	37.00
47.37	37.67	47.56	52.13	52.42	51.21	49.80	48.52	47.41	46.40	45.46	44.56	43.68	42.81	41.95	41.11	40.27	39.44	38.62	37.81	37.00
50.53	60.15	57.39	54.74	52.57	50.83	49.45	48.32	47.35	46.44	45.56	44.67	43.79	42.91	42.04	41.18	40.33	39.49	38.66	37.83	37.00
53.68	60.69	56.69	53.79	51.63	50.13	49.07	48.22	47.40	46.56	45.68	44.79	43.89	42.99	42.11	41.24	40.38	39.53	38.69	37.84	37.00
56.84	60.00	54.96	51.68	50.08	49.46	49.02	48.42	47.63	46.73	45.79	44.86	43.95	43.05	42.17	41.29	40.43	39.57	38.71	37.85	37.00
60.00	48.14	44.08	47.71	49.94	50.39	49.82	48.85	47.80	46.78	45.82	44.89	43.99	43.10	42.21	41.34	40.46	39.59	38.73	37.86	37.00