# NUMERICAL SIMULATION OF HEAT TRANSFER IN BLOOD VESSELS

SALAHUDDIN AZRAIE

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Universiti Teknologi Malaysia

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# ABSTRACT

There is inadequate work done on tapered and stenois blood vessel under thermotheraphy, experimental studies being impossible to be conducted since the system is unlike mechanical system which could be modeled in the lab. In this study, the blood flow and heat transfer in an artery under various heating conditions have been numerically simulated. Three different cases of blood vessels are considered: straight vessel, converging tapered vessel and stenois vessel. Constant heat flux was applied at several intensities in each case. It was shown that the flow simulated at the vena contracta is analogous to the flow in a converging-diverging nozzle. However, the dimensionless center velocity at outlet region was found to be higher than that at the inlet region which could be due to the slow recovery of pressure after the stenois region. The local Nusselt number fluctuated at both the downstream and upstream which could have been caused by recirculation as the flow entered and exit the stenois region. Results in general have shown that blood flow in biological systems may well behave like the mechanical systems.

# ABSTRAK

Kajian terhadap pembuluh darah meruncing dan pembuluh ‘stenois’ dalam keadaan terapi panas adalah kurang. Ujikaji adalah mustahil dilakukan kerana tidak seperti sistem mekanikal, model sistem untuk ujikaji tidak boleh dilakukan di dalam makmal. Dalam kajian ini, pengaliran darah dan pemindahan haba di dalam saluran arteri di bawah pelbagai keadaan pemanasan telah disimulasikan secara berangka. Tiga kes pembuluh darah telah dilihat: pembuluh lurus, pembuluh meruncing dan pembuluh ‘stenois’. Pelbagai kekuatan fluks haba kenaan telah dikaji dalam setiap kes. Hasil simulasi menunjukkan bahawa aliran pada vena kontrakta adalah seperti aliran di dalam muncung tumpu capah. Halaju pusat tak berdimensi pada kawasan alur keluar didapati lebih tinggi daripada yang terdapat pada kawasan alur masuk. Ini mungkin disebabkan oleh pemulihan perlahan tekanan selepas melewati kawasan stenois. Angka Nusselt tempatan turun-naik di hulu dan hilir kawasan stenois yang mungkin disebabkan oleh edaran semula apabila aliran memasuki dan keluar dari kawasan tersebut. Keputusan secara umumnya menunjukkan bahawa aliran darah dalam sistem biologi berkelakuan sama seperti aliran sistem mekanikal.

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# LIST OF SYMBOLS

| | |
|---|---|
| $c_p$ | Specific heat |
| $d$ | Diameter |
| $\vec{F}$ | External body forces or any user-defined sources |
| $h$ | Enthalpy (ideal gases / incompressible flows) |
| $h$ | Heat transfer coefficient |
| $I$ | Unit tensor |
| $\vec{J}_j$ | Diffusion flux of species $j$ |
| $k_{eff}$ | Effective conductivity |
| $p$ | Static pressure |
| $q$ | Constant heat flux |
| $r$ | Radial coordinate / radius |
| $S_h$ | Heat of chemical reaction and any other user-defined heat sources |
| $S_m$ | Mass added to the continuous phase from the dispersed second phase or any user-defined sources |
| $t$ | Time |
| $T_m$ | Fluid bulk temperature |
| $T_w$ | Wall temperature |
| $U_c$ | Axial velocity at center of tube |
| $U_m$ | Fluid average inlet velocity |
| $x$ | Axial coordinate |
| $\rho$ | Fluid density |

| | |
|---|---|
| $\rho \vec{g}$ | Gravitational body force |
| $\overline{\overline{\tau}}$ | Tensor stress |
| $\mu$ | Molecular viscosity / fluid dynamics viscosity |
| $\vec{v}$ | Fluid velocity |
| $v_r$ | Radial velocity |
| $v_x$ | Axial velocity |
| $\nabla \vec{v}^T$ | Effect of volume dilation |

**Non-dimensional parameter**

| | |
|---|---|
| Nu | Nusselt number |
| Pr | Prandlt number |
| Re | Reynolds number |

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# CHAPTER I

# INTRODUCTION

## 1.1 Introduction

The understanding of the function of the circulation system under both normal and abnormal conditions, designing cardiovascular artificial devices as well as diagnosing and treating disease is not complete without the full understanding of blood flow. The first attempt to formulate the governing equation of motion of blood in an artery was made by Euler in 1775. Before the age of computer, the analytical solutions were done with much considerable simplifications. Following the introduction of computers, blood flow equation can be treated with fewer simplification and enable the theoretical results to be close to experimental ones (Hunter, 1972).

Since the earlier attempt by Euler until recently development, many models of blood and blood flow have been introduced by researchers. Earlier researchers tend to assume blood as a Newtonian fluid which is flowing in a rigid tube wall in order to make the calculation easier. Later on, non-Newtonian fluid assumption was applied to study blood flow in tube with less than 1mm diameter. Lattice

Boltzmann approach was introduced around year 2009 to cater to non-Newtonian complexity of blood flow (Ashrafizaadeh and Bakshaei, 2009). Currently, the study of blood flow in a straight tube involves complex simulation by introducing bifurcation and stenosis effects. Heat transfer and magnetic field effect on blood flow have also been introduced to bring more understanding about blood rheology.

Higher heart failure mortality in most developed countries (Espino et al, 2006) makes the study of blood flow significantly important. Certain diseases lead to heart failure due to the changing of blood flow pattern in blood vessels. From a microscopic point of view, interaction between blood particles (red blood cells, white blood cells and platelets) and bifurcation walls can lead to changing in velocity patterns especially when there are irregularities in the said regions such as fat or stenosis.

Blood contains many enzymes and hormones, and transports oxygen and carbon dioxide from the lung to the cells of the tissues. Blood circulation also plays an important role in thermoregulation and mass transport. The quantitative prediction becomes more significant in human thermal comfort, drug delivery and noninvasive measurements research. Earlier heat transfer analysis introduced non-invasive measurement of glucose in blood by means of measuring heat generation from glucose itself. Another significant importance of heat transfer analysis in blood vessels to surrounding walls or tissues is to understand more on drug penetration in tumor affected tissues.

Thermal therapy is one of the widely used methods in treating tumor. Various method of heating is introduced in medical field to enhance necrosis rate of tumor such as ultrasound, laser irradiation, and laser ablation. Hyperthermia therapy method is used to enhance the effect of radiotherapy and chemotherapy (Yuan, 2009). These methods require no surgery to perform. Other method that requires small surgery is radiofrequency tumor ablation (Santos et al, 2008). All abovementioned methods are aim to kill tumor affected tissue. However, heating does change behavior of blood flow and heating effectiveness relies on blood

vessels geometry. Therefore, further understanding of heating effects on blood flow in various blood vessels geometry is indeed important to improve tumor treatment under thermal therapy.

## 1.2 Literature Review

J.P. Hunter is probably the first to formulate and solved numerically the governing equations of blood flow in a nonlinear viscoelastic artery in 1972 in his Masters' thesis (Hunter, 1972). He assumed that the blood was Newtonian, homogenous and incompressible. In his model, blood was assumed to flow in a cylindrical tube under non-turbulent flow condition with an elastic artery wall. The artery wall showed both elastic and collagen fiber behavior. These two behaviors lead to a non-linear time dependent stress-strain relationship. The artery wall became stiffer at higher transmural (through the wall of an organ) pressure due to higher Young's modulus value. In vito testing was used to obtain experimental data to get the relationship between transmural pressure and arterial radius of the wall. According to Hunter, an empirical approach was better than synthetic approach using finite elasticity theory since the synthetic approach implied the artery wall material is homogenous, isotropic and incompressible. Furthermore, Hunter also considered blood flow through bifurcation in order to fully describe his heart-aorta model. The computational blood flow through bifurcation was solved using FORTRAN software by adopting finite difference approach. Heat transfer in blood flow was mentioned in the last chapter. The general one dimensional heat equation was used to calculate the transfer of heat along the artery assuming no heat loss to the surroundings. Hunter did not consider any heat transfer between bloods to the artery wall.

Khaled et al (Khaled et al, 2003) reviewed transport theories in porous media and its application in biological tissues. Mass diffusion and different convective flow models are used to study the transport theories. Development of bio-heat equation was analyzed. The most appropriate bio-heat model for heat transfer in biological tissues was found in the theory of porous media.

Tsubota et al (Tsubota et al, 2006) introduced a new approach to describe the behavior of blood flow in 2005 called particle method. Blood was assumed to be incompressible and Newtonian fluid and modeled as an assembly of discrete particles. Blood was also assumed to be homogenous fluid from macroscopic point of view. Tsubota et al argued that continuum mechanics approach such as finite difference method (FDM), finite volume method (FVM), and finite element method (FEM) can be used to analyze blood flow numerically. One of obvious limitation for this approach is the simulation is its two-dimensional analysis instead of three-dimensional. However, his simulation results are yet to be verified by experimental results. Furthermore, there is no mention of heat transfer analysis in blood vessel using this particle method.

Blood flow and heat transfer in human finger was studied by He et al in 2008 (He et al, 2008). In his blood flow modeling, he simulated the blood flow in large vessels with the diameter larger than or equal to 1mm. One-dimensional flow model was used for this case. Darcy model in porous medium approach was assumed in his blood flow modeling for micro-vessels case. Finite element model was used to model a human finger. Magnetic resonance imaging (MRI) method was used to obtain a geometric model of a human finger and different sequences of images were taken to simulate flow of blood and heat transfer. From his images data, the inflow velocity in the artery was found to be 19cm/s and in the vein3.5cm/s. Reynolds number was 50 for this case when the arterial velocity was the reference velocity. Ying He concluded that porous media transport model provided good result to heat transfer analysis in living tissues (in this case, human finger) using unified energy equation.

Numerical modeling of blood flow in a variable shape artery wall was performed by Mukhopadhyay and Layek (Mukhopadhyay and Layek, 2008). In their study, blood was assumed to be a Newtonian fluid and the flow was simulated in the rigid artery wall under steady state situations. Three shapes of the stenois (abnormal narrowing in a blood vessel) were used in this modeling and the shape was symmetric as well as asymmetric about the middle cross sectional area. Mukhopadhyay et al agreed in their research that blood could be treated as a Newtonian fluid since the viscosity coefficient of blood approaches a constant value under relatively large shear rates. Furthermore, the diameter of the rigid tube used in the modeling was equivalently the same as the diameter of a large vessel in which Newtonian fluid condition was satisfied. Hemodynamic factors in the rigid tube like wall shear stress, pressure and velocity were analyzed. No heat transfer analysis was performed under this rigid artery wall assumption with variable shape of stenois.

Thermal effect on tumor was studied by Horng et al (Horng et al, 2007) using pulsatile blood flow. Cyclic effect of heart beat was implemented by using a sinusoidal pulsatile velocity profile. Horng et al judged from their literature that blood flow in all arteries undergo pulsatile flow due to the heart pump nature. The energy transport equation with Pennes's bioheat equation was used to solve the heat transfer between blood vessels and surrounding tumor tissues. The blood flow was modeled with assumptions of incompressible, laminar and Newtonian fluid. Blood vessel was modeled as a rigid artery wall in perfect cylindrical shape. Other blood properties such as thermal conductivity; specific heat and perfusion mass flow rate can be found in their literature. They concluded in their study by suggesting that steady uniform velocity profile and pulsatile velocity profile for blood flow exhibited minor differences on thermal analysis. Heat transfer analysis to the surrounding tissues was done in their study with an assumption of inelastic artery wall.

The study of dynamics response of heat and mass transfer in blood flow through bifurcation arteries was done by Chakravarty and Sen (Chakravarty and

Sen, 2005). A mathematical model of the response was developed under the assumption of Newtonian fluid. Navier-Stokes equation was used to describe nonlinear unsteady flow phenomenon and heat conduction and convection-diffusion equations were used to performed thermal analysis. In this study, the artery wall was assumed to be elastic on local fluid mechanics but not on the stresses and strains in the wall itself. The wall motion effect on velocity profile of blood flow was found to be insignificant. Temperature profiles at apex of arterial bifurcation also gave insignificant difference when considering wall motion compared to the rigid wall. In his concluding remark, there was significant reduction in heat flux magnitude when the arterial wall was considered as rigid.

Hyperthermia therapy simulation in biological tissue was done by Yuan (Yuan, 2008). An equivalent heat transfer coefficient in a porous model was done by numerical analysis. In this study, all arterial blood vessels were assumed to be straight and treated as porous medium, constant heat transfer coefficient and blood velocity were used, and thermal properties for tissues and blood were treated as isotropic. Ultrasound was used as a source of energy input for hyperthermia treatment. The whole domain of calculation was considered as an assembly of repeated hexagon units. Tri-Diagonal Matrix Algorithm was employed to solve two-equation porous model for blood and tissue and Pennes's bio-heat transfer equation to predict the temperature distribution. Yuan concluded in his summary that a decrease in vessel diameter increases the equivalent heat transfer coefficient. The equivalent heat transfer coefficient also is not dominated by blood velocity and heating conditions. Three equivalent heat transfer coefficient were calculated for three different vessel diameters. Yuan did not consider in his study to for expanding or narrowing vessel diameter or non-symmetric blood vessel.

Cooling effect of thermally significant blood vessels in perfused tumor tissue during thermal therapy was done by Shih et al (Shih et al, 2006). A single blood vessel with rigid wall inside and throughout the perfused tumor tissue was used as computational domain. The velocity profile in the blood vessel was assumed to be uniform. The temperature of blood flow and tissue were governed by

the energy transport equation. During thermal simulation, ultrasound was used as source of heat power and the heat absorption rate of blood is assumed to be one-tenth of tissue. Heating power density and heating durations were varied while the absorbed total energy density was kept constant during the simulation. Shih et al concluded that short duration and high intensity heating method can eliminate the cooling the cooling effect of the blood vessels 0.2mm in diameter. Cooling effect was stronger for blood vessel larger than 0.2mm diameter and led to incomplete necrosis even though double heating power or density was used. Shih also did not consider in his study to for expanding or narrowing vessel diameter or non-symmetric blood vessel.

Radiofrequency electric current is used in radiofrequency tumor ablation procedure. An active electrode is inserted by mean of surgery and radiofrequency energy is applied to heat the surrounding tissue. Santos et al (Santos et al, 2008) studied the effect of variable heat transfer coefficient on tissue temperature next to a larger vessel during radiofrequency tumor ablation. In his journal, a large artery 10mm diameter was used and an electrode was put at two different distances away from the artery. The blood was assumed as a Newtonian fluid and the flow was assumed to be laminar. The vessel of artery was assumed to be straight with constant blood velocity. Both constant and variable of the convective heat transfer coefficient were simulated. The convective heat transfer coefficient was increased initially and rapidly up to 6000W/m$^2$K followed by a sharp decrease to 554W/m$^2$K for 1mm distance configuration. The convective heat transfer coefficient was increased initially and rapidly up to 7000W/m$^2$K followed by a sharp decrease to 336W/m$^2$K for 5mm distance configuration. Santos et al concluded that assumption of constant convective heat transfer coefficient sufficient enough to produce precise result for thermal procedure more than 2 minutes.

The preceding paragraphs described some of the past studies related to blood flow. Figure 1.2.1 shows blood flow major categories.

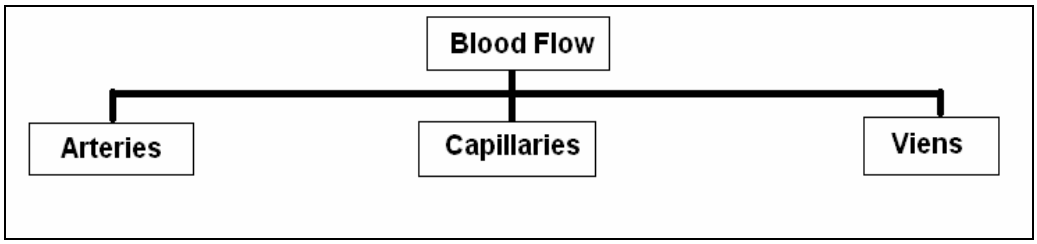


**Figure 1.2.1:** Blood flow categories

Figure 1.2.2 shows summarized most of the work associated with blood flow completed.

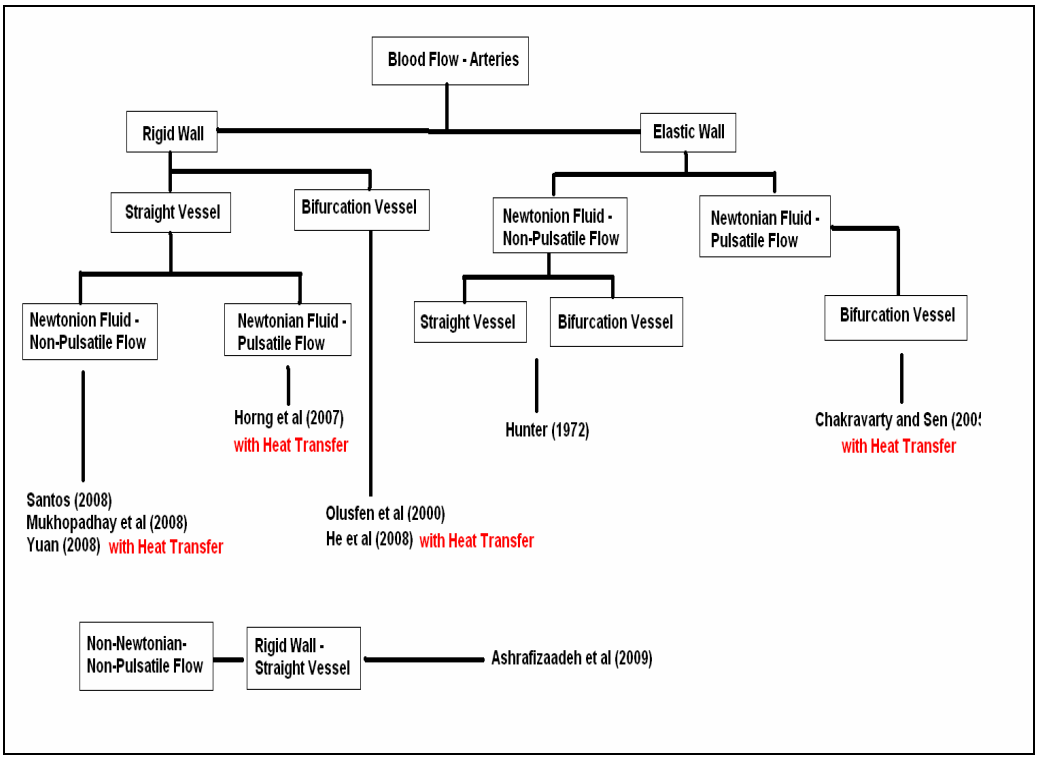


**Figure 1.2.2:** History of blood flow studies in arteries

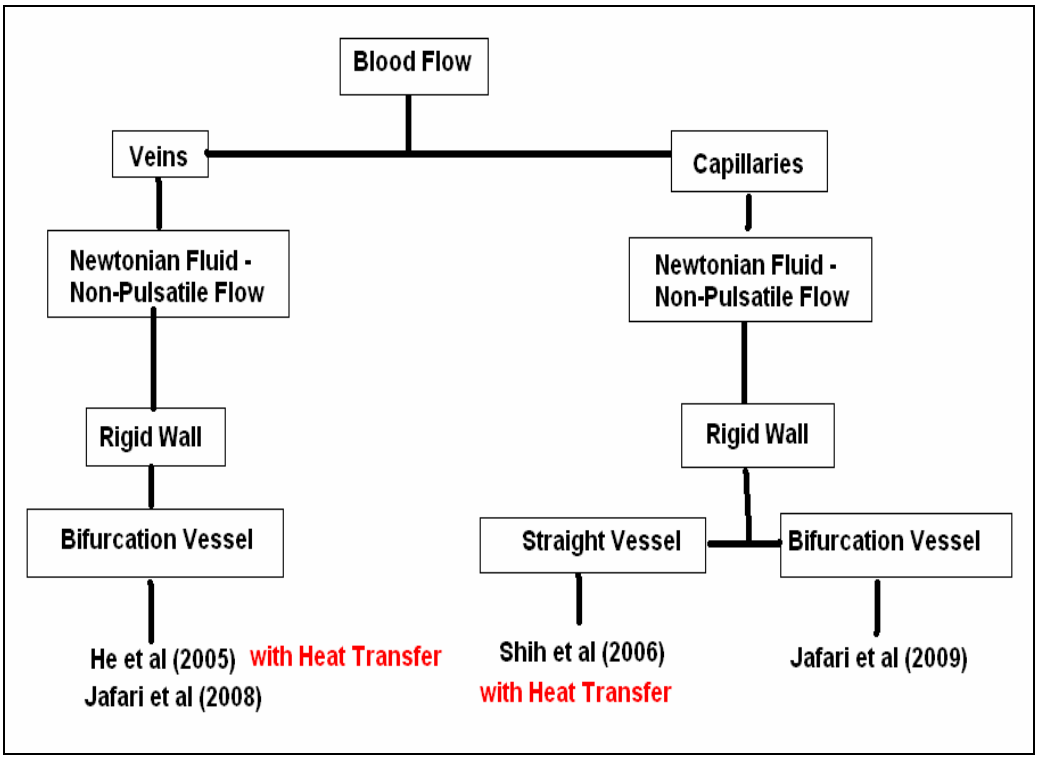


**Figure 1.2.3:** History of blood flow studies in veins and capillaries

Figure 1.2.2 and Figure 1.2.3 show that most of heat transfer studies were done with straight vessel assumption. He et al (He et al, 2008) did performed heat transfer study by considering bifurcation vessel but He assumed that both parent and daughter vessels were straight vessel. Apparently, there is inadequate work done on tapered and stenois blood vessel under heating condition.

## 1.3 Objective

The objective of this study is to numerically simulate the blood flow and heat transfer in an artery under heating conditions.

## 1.4 Scope of Study

The scope of this study will involve:

1 – Simulation of the normal blood flow in an artery.
2 – Repeating (1) under abnormal condition of heating (i.e. chemotherapy, thermotherapy) at various degrees.
3 – Repeating (1) for a tapered channel flow and stenois (abnormal narrowing) channel flow.

# REFERENCES

Ashrafizaadeh, M, and Bakshaei, H, A Comparison of Non-Newtonian Models for Lattice Boltzmann Blood Flow Simulations, Computer and Mathematics with Application (2009)

Bijan, A, Convective Heat Transfer, Wiley Interscience Publication (1984)

Chandran, K.B., Yoganathan, A.P., and Rittgers, S.E., Biofluid Mechanics: The Human Circulation, Taylor and Francis (2007)

Chakravarty, S. and Mandal, P.K, Two Dimensional Blood Flow through Tapered Arteries under Stenotic Conditions, International Journal of Non-linear Mechanics (2000)

Chakravarty, S, and Sen, S, Dynamics Response of Heat and Mass Transfer in Blood Flow through Stenosed Bifurcation Arteries, Korea-Australia Rheology Journal, Vol 17, No. 2 (June 2005)

Espino, D.M., Watkins, M.A., Shepherd, D.E., Hukins, D.W., and Buchan, K.G., Simulation of Blood Flow through Mitral Valve of the Heart: A Fluid Structure Interaction Model, COMSOL Users Conference (2006) Birmingham

Fluent Incorporation, Fluent 6.2 User's Guide, Fluent Incorporation (2005)

Goshdastidar, P.S, Heat Transfer, Oxford University Press (2004)

Jafari, A., Mousavi, S.M., and Kolari, P, Numerical Simulation of Blood Flow: Part 1: In Micro-vessels Bifurcations, Communications in Nonlinear Science and Numerical Simulation 12 (2008) 1615-1626

Jafari, A, Zamankhan, P, Mousavi, S.M., Kolari, P, Numerical Investigation of Blood Flow. Part II: In Capillaries, Communication in non-Linear Science and Numerical Simulations 14 (2009) 1396-1402

He, Y, Liu, H, Himeno, R, Sunaga, J, Kakusho, N, and Yokota, H, Finite Element Analysis of Blood Flow and Heat Transfer in an Image-based Human Finger, Computer in Biology and Medicine 38 (2008) 555-562.

Horng, T.L, Lin, W.L, Liauh, C.T, Shih, T.C, Effects of Pulsative Blood Flow in Large Vessels on Thermal Dose Distribution during Thermal Theraphy, Medical Physic 34 (4) (April 2007)

Hunter, P.J, Numerical Simulation of Arterial Blood Flow, University of Auckland, Masters Thesis (1972)

Kakac, S and Yener, Y, Convetive Heat Transfer, CRC Press (1995)

Khaled, A.R.A, and Vafai, K, The Role of Porous Media in Modeling Flow and Heat Transfer in Biological Tissues, International Journal of Heat and Mass Transfer 46 (2003)

Mukhopadhay, S and Layek, G.C, Numerical Modeling of a Stenosed Artery using Mathematical Modeling of Variable Shape, Applications and Applied Mathematics: An International Journal Vol. 3, No. 2 (December 2008) pp. 308-328

Olufsen M.S, Peskin, C.S, Kim, W.Y, Pedersen, E.M, Nadim, A, and Larsen, J, Numerical Simulation and Experimental Validation of Blood Flow in Arteries with Structured-Tree Outflow Conditions, Annals of Biomedical Engineering, Vol. 28, pp. 1281-1299 (2000)

Qioa, A, and Liu, Y, Medical Application Oriented Blood Flow Simulation, Clinical Biomechanics 23 (2008) S130-S136

Santos, I.D, Haemmerich, D, Pinheiro, C.D.S, Rocha, A.F.D, Effect of Variable Heat Transfer Coefficient on Tissue Temperature Next to a Large Vessel during Radiofrequency Tumor Ablation, Biomedical Engineering Online, (2008)

Shih, T.C, Liu, H.L, Horng, T.L, Cooling Effect of Thermally Significant Blood Vessels in Perfused Tumor Tissue during Thermal Therapy, International Communications in Heat and Mass Transfer 33 (2006) 135-141

Tsubota, K.I, Wada, S, Kamada, H, Kitagawa, Y, Lima, R, and Yamaguchi, T, A Particle Method for Blood Flow Simulation – Application to Flowing Red

Blood Cells and Platelets, Journal of Earth Simulator, Volume 6, (March 2006) 2-7

Waite, L and Fine, J Applied Bio-fluid Mechanics, McGraw Hill (2007)

Yuan, P, Numerical Analysis of an Equivalent Heat Transfer Coefficient in a Porous Model for Simulating a Biological Tissue in a Hyperthermia Therapy, International Journal of Heat and Mass Transfer 52 (2008) 1734-1740