Analysis of Ambient Temperature Effect on Blood Viscosity and Blood Pressure Drop

A dissertation submitted towards the partial fulfillment
of the requirements for the award of degree of

Master of Engineering

In

Electronic Instrumentation & Control Engineering

Submitted by

Raghu Kalia
Roll No: 801251016

Under the supervision of

Dr.Sunil Kumar Singla
Assistant Professor, EIED

ELECTRICAL AND INSTRUMENTATION ENGINEERING DEPARTMENT
THAPAR UNIVERSITY
(Established under the section 3 of UGC act, 1956)
Patiala, 147004, Punjab, India

JULY – 2014

CERTIFICATE

This is to certify that the work presented in this dissertation entitled "**Analysis of Ambient Temperature Effect on Blood Viscosity and Blood Pressure Drop**" submitted by Mr. Raghu Kalia in partial fulfillment of the requirement for the award of the degree of Master of Engineering in Electronic Instrumentation and Control Engineering at Thapar University, Patiala is an original record of the candidate's own work carried by him under the worthy supervision of **Dr.Sunil Kumar Singla**. The matter embodied in this report has not been submitted in any other University/Institute for the award of any degree.

Date: 18/07/2014.

Place: Patiala

Raghu Kalia

Raghu Kalia

(801251016)

Thapar University, Patiala

It is certified that the above statement made by the student is correct to the best of my/our knowledge and belief.

(Sunil Kumar Singla)

Assistant Professor

EIED

Thapar University, Patiala

Countersigned by

(Ravinder Agarwal)

Professor and Head

EIED

Thapar University, Patiala

(S.K Mohapatra)

Dean of Academic Affairs

Thapar University, Patiala

ACKNOWLEDGEMENT

The real spirit of achieving a goal is through the way of excellence and discipline. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various personalities.

Fist of all, I render my gratitude to the ALMIGHTY who bestowed self-confidence, ability and strength in me to complete this work.

With deep dense of gratitude I express my sincere thanks to **Dr.Prakash Gopalan, Director**, Thapar University for his valuable support that made me a consistent performer.

I am grateful to **Dr.S.K. Mohapatra, Dean of Academic Affairs** for his constant encouragement that was of great importance in the completion of this dissertation.

I am thankful to **Dr.Ravinder Agarwal, Professor and Head** of Electrical and Instrumentation Department who has been a constant source of inspiration for me throughout this work.

I am also thankful to our PG Coordinator **Dr.Mandeep Singh, Associate Professor** for his valuable support.

With deep dense of gratitude I express my sincere thanks to my esteemed and worthy supervisor **Dr.Sunil Kumar Singla, Assistant Professor** in the Department of Electrical and Instrumentation Engineering for his valuable guidance in carrying out this work under his effective supervision, encouragement, enlightenment and cooperation.

I would also like to thank my dear friend **Sandeep Kumar** as most of the novel ideas found in this are the result of our numerous simulating discussions.

I would like to thank my parents and elders for their constant support and encouragement.

I am thankful to all my friends for their valuable suggestions.

Place: TU, Patiala Raghu Kalia

ABSTRACT

Blood pressure drop in humans considering the effect of ambient temperature variation due to various climatic and environmental changes is such a phenomenon which is still unexplored. By implementing the developed algorithm in the blood pressure measuring devices can improve their performance. In this study, a comparison is made between the blood pressure drop readings for both men and women considering the effect of ambient temperature change and employing various heat transfer modes. For a group of healthy individuals within the age group of 27$\pm$4 years, height ranging 170$\pm$5 cm and weight 73$\pm$5 kg (means$\pm$SD), the results presented and discussed here are for both men and women with same height 170.6 cm and weight 73 kg. According to the mathematical model created and after the implementation of the developed algorithm, it is observed that ambient temperature variation certainly affects arterial blood pressure drop in the brachial artery with length 22.22 cm. The range of systolic blood pressure drop values in case of men lies between 2.7561 mmHg to 6.5470 mmHg and the range of diastolic blood pressure drop lies between 0.3802 mmHg to 0.9032 mmHg. For women, the range of systolic blood pressure drop values lies between 2.4996 mmHg to 5.9356 mmHg and for diastolic blood pressure drop, this range lies between 0.40233 mmHg to 0.95539 mmHg. The obtained values for blood pressure drop can be added as a correction factor to the readings presented as final output by the current blood pressure measuring devices in order to obtain the correct systolic and diastolic blood pressure values. Hence, this study is termed as blood pressure drop-correction factor (BPD-CF). This analysis helps to infer about the functioning of the heart and its cardiac cycle.

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NOMENCLATURE

h_b	convective heat transfer coefficient of blood, W/ (m^2k)
h_c	natural convective heat transfer coefficient of skin, W/ (m^2k)
h_r	radiative heat transfer coefficient of skin, W/ (m^2k)
h_a	heat transfer coefficient of artery, W/ (m^2k)
h_{air}	natural convective heat transfer coefficient of air, W/ (m^2k)
A_a	area of artery, m^2
A_s	skin surface area of arm, m^2
r_0	outer radius of artery, m
r_i	inner radius of artery, m
l	length of artery, m
k_b	thermal conductivity of blood, W/ (m k)
k_a	thermal conductivity of artery, W/ (m k)
k_e	thermal conductivity of epidermis, W/ (m k)
k_d	thermal conductivity of dermis, W/ (m k)
k_s	thermal conductivity of subcutaneous tissue, W/ (m k)
δ_a	thickness of artery, m
δ_e	thickness of epidermis, m
δ_d	thickness of dermis, m
δ_s	thickness of subcutaneous tissue, m
ρ_b	density of blood, kg/m^3
T_b	blood temperature, °C
T_s	skin surface temperature, °C
T_a	ambient temperature, °C
H	haematocrit, %
t	external temperature, °F
vis_{plasma}	plasma viscosity, Ns/m^2
vis_{blood}	blood viscosity, Ns/m^2
P_d	pressure drop, N/m^2
Q	volumetric flow rate, m^3/s
U	overall heat transfer coefficient, W/ (m^2k)
m	mass flow rate, kg/s

β	temperature coefficient, °C^{-1}
C_p	specific heat of human blood
BSA	body surface area, m^2
M_{sys}	Systolic blood pressure drop in men, mmHg
W_{sys}	Systolic blood pressure drop in women, mmHg
M_{dia}	Diastolic blood pressure drop in men, mmHg
W_{dia}	Diastolic blood pressure drop in women, mmHg
M_{Tb}	Temperature of blood in men, ℃
W_{Tb}	Temperature of blood in women, ℃
Ta	Ambient temperature, ℃
M_{visbl}	Viscosity of blood in men, Ns/m^2
W_{visbl}	Viscosity of blood in women, Ns/m^2

CHAPTER 1

INTRODUCTION

In clinical medicine, blood pressure measuring devices has a large market. When selecting a blood pressure measuring device for consumers, accuracy is always of prime importance. Both manual and automatic sphygmomanometers play a significant role in measurement of arterial blood pressure. Blood pressure measuring devices also play a vital role as clinical diagnostic instruments and in patient monitoring systems. Due to their operation in such crucial tasks, the primary and the foremost requirement is the device to be accurate in all aspects. To improve accuracy and in order to improve the functioning of blood pressure measuring devices, an attempt is made to present and discuss a new approach which may be added to the blood pressure measuring instruments available in the market.

1.1 Blood Pressure Measurement

There are two types of sphygmomanometers: manual, which include aneroid and mercury devices; and automated, which include devices for self measurement of blood pressure and for clinical use [35]. Manual sphygmomanometer includes non-invasive blood pressure measuring method using a sphygmomanometer and a stethoscope known as ausculatory method. It involves listening to a particular sound while performing measurement. Automated sphygmomanometers includes blood pressure measurement at the upper arm which use oscillometric technique, require no manual listening to korotkoff sound and has an automatic functioning of the cuff occluding the brachial artery. All these devices play a significant role in blood pressure measurement thus are very important from clinical viewpoint as accuracy is always of prime importance when selecting a blood pressure measuring device [35]. Arterial blood pressure which is measured at person's upper arm is a measure of the blood pressure in the brachial_artery which is one of the major arteries in the upper arm [34]. As the blood flows inside the artery, it exerts force on arterial walls. This force is sensed by an electronic pressure sensor (transducer) which is used to sense and observe cuff pressure oscillations, use of electronics with the function to automatically interpret them, and provision of automatic functioning of the cuff with the blood pressure measuring instrument. All such devices give final output blood pressure readings in terms of systolic and diastolic values.

Systolic and diastolic blood pressure values are reported in millimeters of mercury (mm Hg), for example 120/80 mm Hg is the normal blood pressure range with 120 mm Hg as systolic pressure drop and 80 mm Hg as the diastolic pressure drop [35]. Value of blood pressure which is pathologically low is called hypotension, and pathologically high is called hypertension. Both hypertension and hypotension have many causes with their values ranging from mild to severe. Thus, blood pressure measuring devices has a large market in self measurement and clinical medicine. Accuracy is always of prime importance when selecting a blood pressure measuring device for consumers. Thus, to improve the accuracy and in order to improve the functioning of blood pressure measuring devices, an attempt is made in this study to present and discuss a new methodology which may be added to the blood pressure measuring instruments available in the market.

1.2 What is Skin?

In terms of both surface area and weight, the largest and the outermost tissue of the body is termed as skin. For an adult, the surface area of skin is approximately 16, 000 cm^2 and it represents about 8% of the total body weight. Skin consists of many components with a very complex structure. Skin is a multi-layered structure made up of cells, fibers and other components. Inside this structure, capillaries, nerves and veins form vast networks. Resulting from chemical and physical reactions, skin performs a variety of functions inside various components [35]. Skin act as a barrier to the external environment which is the major function of the skin. It helps to regulate body temperature, thus maintain overall thermal balance of the body.

1.3 Human Skin Appearance

Cellular level elements and various skin layers constitute the physio-anatomical structure of skin. Here, we focus only on those skin components that have a contribution to its appearance which is measureable. The smallest components of skin are referred as micro scale, larger as meso scale and the largest components are referred as macro scale. In this study, we consider only micro scale components. These components are very small in sizes which are barely visible to the naked eye [33]. Due to optical interactions with the incident light, these elements represent visual properties. From heat transfer viewpoint, the dominant effects produced at this scale are conduction, convection and radiation. All the cellular level elements collectively constitute several primary skin layers: epidermis, dermis and subcutaneous. The outermost layer of skin i.e. epidermis provides a barrier from external environment. Beneath the epidermis is the dermis which is the tough connective tissue between epidermis and subcutaneous layer and contains sweat glands. Subcutaneous tissue is made of fat present below dermis. These layers differ in structures and constituents and hence they differ in physiological characteristics [19]. For example, it is seen in Table 1.1, epidermis is a very thin layer (80 µm on average) composed mainly of cells. The dermis is a thicker layer (2000 µm on average) composed of more fibers as compared to the epidermis. The thickness of the subcutaneous tissue is about 18000 µm. These physio-anatomical differences influences the heat propagation through these layers and lead to very different heat transfer effects.

Skin layer	Thickness, δ (m)
Epidermis	0.000008
Dermis	0.002
Subcutaneous tissue	0.018

Table 1.1 Thickness values for different skin layers [19]

Various functions are performed by skin layers such as protection from non-favorable climatic conditions, thermoregulation of the body and maintaining core temperature. As the ambient temperature decreases, the blood vessels aid heat loss and with increase in ambient temperature, the constricted blood vessels results in reduction of the subcutaneous blood flow thus conserving heat inside.

1.4 Heat Transfer

Thermal energy exchange between various physical systems by dissipating heat depending on temperature and pressure is termed as heat transfer. It plays an important role in maintaining the overall thermal balance by transferring heat through different fundamental modes. The amount of heat transfer depends on how a particular process occurs in accordance with the variation between initial and final state of that particular process. Various heat transfer modes collectively contribute to aid heat transfer process to attain the resultant temperature as the final output. The amount of heat transfer is calculated by heat transfer coefficient.

1.5 Heat Transfer Modes

In addition to heat transfer process, three modes to aid heat transfer play a significant role in achieving the thermal balance of the body. Conduction, convection and radiation contribute together to heat transfer process. Conduction of heat between two bodies in direct contact with each other is the heat conduction mode. In this, flow of heat is from one body to the other with the basic requirement of their direct contact with each other. Heat transfer through intervening matter without any motion of the matter is the conduction. Fluid in motion causing heat transfer is the convection mode of heat transfer. In this, the transfer of heat is through bulk transfer with fluid of non-uniform temperature. Convection differs from conduction as in conduction; the heat moves itself while in convection, fluid with hot portions results in movement through fluid body. As a result, mixture of hot and cold fluid takes place and heat is transferred more rapidly than by conduction. Presence of matter is not necessary in radiation which is the third and the simplest mode of heat transfer. All the three modes play a significant role in achieving the overall thermal balance of the body.

1.6 Heat Transfer Coefficient

Convective heat transfer has various quantitative characteristics. One of the very important characteristic is the heat transfer coefficient which may be defined as the characteristic between a fluid medium and the surface over which the fluid flows. Heat transfer coefficient is represented by symbol “h”. Various types of heat transfer coefficients are conductive, convective and radiative. All the three play a significant role in heat transfer operation, thus aid in implementation to various operations.

1.7 Temperature effect on pressure drop

As the temperature increases, the viscosity of the fluid decreases and vice-versa. This variation in temperature results in change of viscosity of fluid, thus affecting pressure drop. Pressure drop is significant parameter which aid to fluid flow. There is variation in pressure drop with fluid flow and is different at various points throughout the flow. Pressure drop depends on viscosity of fluid. With increase in viscosity of fluid, pressure drop decreases and as the viscosity decreases, pressure drop increases. There is direct relation between temperature-viscosity and viscosity-pressure drop. Variation in temperature causes change in viscosity of fluid and this change in fluid viscosity varies pressure drop. From this discussion, it may be said that variation in temperature results in pressure drop change and is a very important concept of this study.

1.8 Blood Pressure

The measure of the force exerted against blood vessel walls by flow of blood is called blood pressure. There is variation in blood pressure during each cardiac cycle and it varies between maximum and minimum pressure. The maximum pressure is called systolic and the minimum pressure is termed as diastolic [34]. The measurement of blood pressure is in millimeters of mercury (mm Hg) and the normal range of measurement lies within 120 mm Hg for systolic (upper) and 80 mm Hg for diastolic (lower) blood pressure readings. Mean blood flow rate is dependent on blood pressure drop. It also depends on the resistance to flow offered by the blood vessels. Many physiological factors influence arterial blood pressure such as exercise, diet, stress, obesity, etc. Viscosity, in other words the thickness of fluid also affects blood pressure. If the viscosity increases or the blood gets thicker, there is an increase in arterial blood pressure drop. As there is decrease in viscosity or the blood gets thinner, there is a decrease in arterial blood pressure drop. Pressure drop is a necessary condition for the flow of blood and there is variation in pressure drop at various points throughout the flow. Measurement of blood pressure in humans is usually taken at upper arm. Blood pressure measuring instruments use a cuff which is tied and inflated across upper arm. In most of the cases, brachial artery is considered suitable to take readings. The cuff is inflated to cause occlusion of brachial artery and the flow of blood is completely disrupted. Deflation of cuff begins slowly so as to resume the blood flow. Systolic blood pressure is the reading obtained at the beginning of the flow. As the flow becomes normal, the diastolic pressure drop is obtained. These pressure drops and readings vary from person to person and depend on age, height, weight and other physiological conditions.

1.9 The Blood and blood pressure drop

Cells of varying sizes get carried by an aqueous solution (plasma) which forms blood. In addition to this, salts, glucose, variety of proteins, dissolved gases also get carried. Blood may be regarded as composition of flexible red cells suspension in plasma (Newtonian fluid) from mechanical viewpoint. Density of blood is similar to water but it differs in viscosity as viscosity of blood is twice the water viscosity. Blood flow plays a significant role in human body functioning. Certain amount of pressure is required for the blood to flow which further aid to pressure drop in the arteries. Arterial blood pressure ranges between a maximum and a minimum value which is also termed as systolic and diastolic arterial blood pressure values. These two values helps to generate the required pressure called the pulse pressure which is the difference between the final readings of systolic and diastolic pressure. Waveforms of pulse pressure depend on arterial network characteristics. There is variation in amplitude and shape depending on the arterial network. Azran Azhim [32] and colleagues studied different velocities of blood flow and blood pressure drop in various subjects the results of which are represented in Fig.1.1.

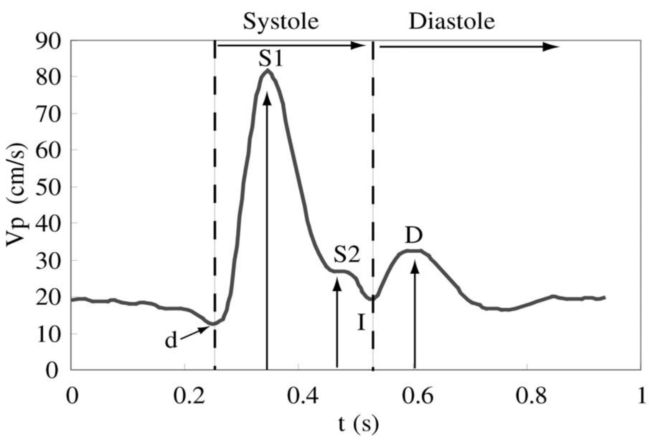

Fig. 1.1 Features of waveform: S1: the first peak systolic velocity wave (peak velocity), S2: the second systolic velocity wave, I: incisura between systole and diastole, D: the peak diastolic velocity wave, and d: the end-diastolic minimum velocity. [32]

They did analysis and discussed various characteristics in cases of men and women. In case of women (n=20), with body height (cm) 157$\pm$5 and body weight (kg) 48$\pm$6, the systolic blood pressure results to be 118$\pm$11 mm Hg and value of diastolic pressure drop to be 73$\pm$11 mm Hg. In case of men (n=30), with body height (cm) 172$\pm$7 and body weight (kg) 64$\pm$9, the systolic blood pressure results to be 127$\pm$14 mm Hg and value of diastolic pressure drop to be 78 $\pm$ 10 mm Hg.

1.10 Pulse Pressure

The difference between the upper and the lower values of human blood pressure which is also termed as the systolic and the diastolic blood pressure readings is calculated to be as pulse pressure [36]. The unit of measurement is in millimeters of mercury (mmHg). It is the force which is exerted by the heart on the arteries each time it contracts. For instance, assuming the blood pressure readings to be systolic/diastolic values as 120/80 millimeters of mercury (mmHg), therefore, the pulse pressure is 40 mmHg. In normal condition, it can be represented mathematically as

$$P_{systolic} – P_{diastolic} = 120mmHg - 80mmHg = 40mmHg$$

1.11 Problem Formulation

Blood pressure in humans gets affected by a variety of factors. The systolic and diastolic pressure drop values may vary with the variation of parameters. Climatic conditions result in change of ambient temperature. Heat transfer and its various modes play a significant role in affecting blood viscosity. As the ambient temperature varies, the heat transfer takes place through various skin layers, fat layer and the artery, thus affecting the viscosity of the blood. Pressure drop changes with variation in viscosity. With the variation in viscosity of blood, the blood pressure drop changes resulting in different values of systolic and diastolic pressure drop due to the effect of change in ambient temperature. Various heat transfer modes play a vital role in affecting blood viscosity. Blood pressure drop depends on blood viscosity to aid blood flow. Using MATLAB, this dissertation aims at:

i. To analyze ambient temperature effect on skin surface temperature, blood temperature and blood viscosity.
ii. To analyze the effect of ambient temperature on readings of blood pressure drop.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

There are various techniques of blood pressure measurement. A lot of research has been performed in this field. There are various areas of convective, conductive and radiative heat transfer of the human body and the effects of posture change are necessary for calculation of heat exchange between human body and its environment. There is outdoor temperature effect on blood pressure and decreasing outdoor temperature may increase blood pressure. Also, there is an increase in blood pressure with the reduction in outdoor temperature. There were two ways of heat dissipation by the skin as predicted by Pennes, one way was through the blood flow and the other was through the conductive heat transfer. Radiant temperature also affects human skin and surface temperature. As there is increase in blood pressure with decreasing ambient temperature which indicates that as there is reduction in value of outdoor temperature, it causes an elevation in final blood pressure drop. With the increase in mean skin temperature, there is reduction in the core temperature threshold resulting in vasoconstriction.

2.2 Related work in this field

Kurazumi et al. [1] studied the areas of convective, conductive and radiative heat transfer of the human body and examined various effects of posture change on the values necessary for calculation of heat exchange between human body and its environment. The author measured the values convective, conductive and radiative heat transfer for the same subject in 9 different postures and concluded that posture certainly have an effect related to the three heat transfer areas considering the human body.

Sakoi et al. [2] examined the thermal comfort in various asymmetric radiant fields for the whole human body in addition for particular local areas on the body, skin temperatures, and sensible heat loss. The author created 35 different thermal environmental conditions in the climatic chamber, studied skin temperatures and heat losses and concluded that the relationship between heat loss and skin temperature depends on environmental thermal uniformity. Relationship of the local skin temperature with the local sensible heat loss is not easy to predict as it varies depending on the environmental thermal nonuniformity.

Huizenga et al. [3] studied the response of core and skin temperature response to cooling and heating of partial- and whole-body. They did measurement of skin and core temperature for different 19 local body parts and during this process, the human subjects were exposed in a controlled environmental chamber and it was found that the core temperature increases as the skin gets cool and decrease as the skin temperature increases. He concluded that in response to cooling of skin, the core temperature increases and in response to skin heating, it decreases.

Kurazumi et al. [4] has developed a behavioral thermoregulation model to predict the mean skin temperature and proved with the relation between mean skin temperature and ETFe (Enhanced conduction-corrected modified effective temperature) that environmental factors affect mean skin temperature. He concluded that there is thermal resistance between skin layers and the core depending on the body weight variations which maintains the core temperature in cold environment and core temperature reduction is easy in hot environment. In this model, it is not assumed that the value for thermal neutral temperature is very low than the value for indoor thermal environment. In a low temperature environment, the actual value difference in which the contraction coefficient of the blood vessel is small is assumed to be large.

Halonen et al. [5] discussed the outdoor temperature effect on blood pressure using a mixed effects model which uses three temperature variables: ambient temperature, apparent temperature and dew point temperature. The author found that decreasing outdoor temperature may increase blood pressure. Apparent temperature may be a more sensitive exposure variable for physiological effects than ambient temperature, but both exposures provided consistent findings in this study.

Madsen Christian et al. [6] achieved associations between environmental conditions and blood pressure and found an increase in blood pressure with the reduction in outdoor temperature. The measurement of blood pressure in winter season was higher in comparison to other seasons. However, when controlling the temperature on the day of the measurement of blood pressure, they found that the seasonal effect could be explained only by the ambient temperature readings and not by any of the seasonal changes. They found that there is linear increase in blood pressure readings with decreasing ambient temperature values which indicates that as there is reduction in value of outdoor temperature, it causes an elevation in final blood pressure drop.

Alperovitch Annick et al. [7] calculated the effects of seasonal variations on blood pressure and found the systolic and diastolic blood pressure values to be different across all the 4 seasons. The measurements of blood pressure were made in those rooms where the temperature in winter season is around 20°C. The influence of indoor temperature within its usual range is less on blood pressure. Although few studies have also examined the association of indoor temperature readings with blood pressure measurement readings but they showed inconsistent findings.

Kenney W. Larry et al. [8] discussed the results when the cardiovascular system has to serve both the temperature and the blood pressure regulation with the ultimate aim of maintaining arterial blood pressure. The author also discussed the determination of overall convective heat transfer requires blood flow through skin, specific heat of blood, and temperature gradient between core and skin. In the case of young and healthy subjects, it may be noted that reduction in arterial blood pressure is very rare during both extreme passive heating and prolonged dynamic exercise in the hot conditions. Also the body temperature does not rise disproportionately because of the reason of compromised skin blood flow.

Brook Robert D. et al. [9] studied the effects of ambient temperature, latitude, altitude, air pollutants and noise on blood pressure and discussed that prolonged exposures to these environmental factors could increase mild hypertension and are important factors to be considered and controlling from clinical point of view. From this study, it may be said that ambient temperature is one of the environmental factors which certainly affect the blood pressure drop in humans.

2.2.1 Calculating body surface area

DuBois D. et al. [10] studied and calculated that the body surface area of humans may be expressed by the equation:

$$BSA\ (m^2) = (wt^{0.425} \times ht^{0.725}) \times 0.007184$$

where weight is in kilograms and height is in centimeters. As the weight and height varies, BSA also varies from person to person.

2.2.2 Calculating skin surface area

Bloomfield Aaron et al. [11] constructed various low cost tactors with the purpose of finding vibrotactile feedback across the whole human arm and discussed that the average skin surface area (A_s) of human arm is about 9% of the body surface area and can be expressed by equation:

$$A_s = (0.09 \times BSA)$$

2.2.3 Brachial artery parameters

K Chauhan et al. [12] studied and discussed that most of the blood pressure measuring devices make use of brachial artery for blood pressure measurement as it is one of the major blood vessels of the human arm with the observed average length of 22.22 cm. They did various observations related to brachial artery present or absent, number of brachial arteries, origin of brachial artery, termination pattern and its various branches with their pattern. The brachial artery divides into radial artery and ulnar artery as seen in Fig. 2.1.

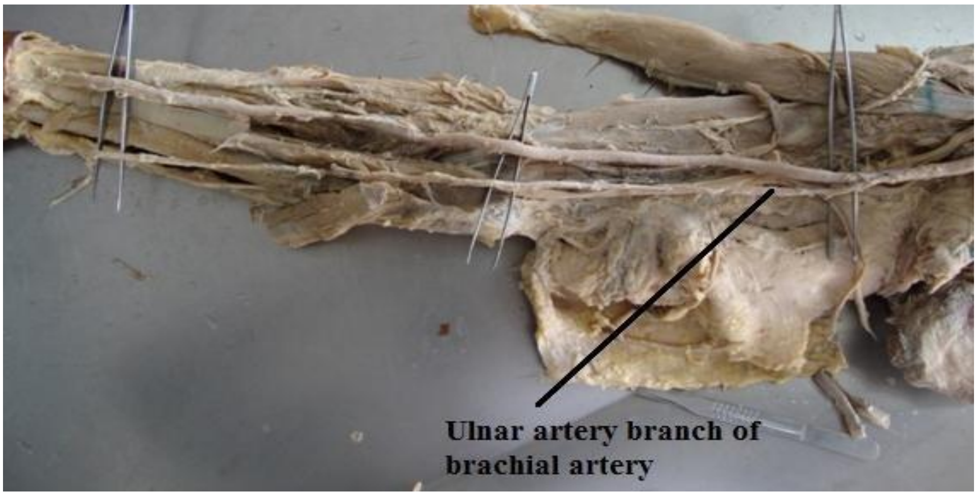

Fig 2.1 Brachial artery dividing into ulnar and radial artery [12]

Gault James H et al. [13] studied and investigated blood flows in brachial artery at a certain flow rate. Mean blood flow rate in brachial artery is averaged 72.7 ml/min. They also investigated various patterns of mean blood flow in brachial artery in the state of rest and the instantaneous changes in the value of mean blood flow during a number of alterations in the forearm vascular resistance (FVR).

Pennes Harry H. et al. [14] presented and discussed that skin plays a significant role in overall thermal balance regulation using various skin thermal properties. There were two ways of heat dissipation by the skin as predicted by Pennes, one way was through the blood flow and the other was through the conductive heat transfer. The measurement of blood flow in brachial artery and the temperatures in the deep forearm were made. Under the experimental conditions, flow of blood acted as warming agent to both the superficial tissues and the forearm tissues. The author asserted that blood flows at core temperature of the body through all tissues in the skin.

Liu Yanfeng et al. [15] studied the radiant temperature effects on human skin and surface temperature. In their study, the experimental data showed that at the same values of radiant temperature, the local skin or surface temperature readings during the process of reduction in radiant temperature were higher as compared to the increase in radiant temperature. During the variation of radiant temperature, the increase or decrease in the values of the mean skin temperature and in the values of the mean surface temperature were seen to decrease gradually from the stable condition, 21℃ per10 min to 21℃ per 5 min. Liu and his colleagues concluded that in comparison to the other parts of the body, the skin temperatures at the hand and foot suffer a great change with environmental temperature and the radiant temperature affect the surface temperature more than the skin temperature.

McLellan Katie et al. [16] examined two important heat dissipation factors i.e. skin moisture and subcutaneous fat and their effects on blood flow and heat exchange. The author also discussed how these factors affect conductive heat exchange and thus affecting the overall thermal balance.
In their study, they expanded the Pennes model by the process of examining subcutaneous fat layer and moisture of skin as the factors of dissipation of heat and considering their effects on exchange of heat and the flow of blood. Measurements were made using thermistors. In their study, they applied heat only for 30 seconds to the skin with the purpose to examine variations in skin temperature.

Cheng Christi et al. [18] studied and discussed that as there is increase in mean skin temperature, there is reduction in the core temperature threshold resulting in vasoconstriction. They found the relationship to be linear between the mean skin and core temperatures. However, there is no significant correlation shivering and cutaneous vasoconstriction. Thus, the blood flow is decreased or restricted to retain body heat. The author concluded that there is reduction in the core temperature with the increasing mean skin temperature due to the process of vasoconstriction and shivering.

2.2.4 Thickness and thermal conductivity of skin layers

Gowrishankar TR et al. [19] investigated and discussed various primary layers of skin which are the dermis, the epidermis and the subcutaneous tissue. These three layers differ in physiological characteristics. For example, epidermis is a very thin layer (80 µm on average) composed mainly of cells. The dermis is a thicker layer (2000 µm on average) composed of more fibers as compared to the epidermis. The thickness of the subcutaneous tissue is about 18000 µm. The three layers also differ in terms of thermal conductivity (k). The different parameters employed and their values are listed in Table 2.1.

Skin layer	Thickness, δ (m)	Thermal conductivity, k W/(m k)
Epidermis	0.000008	0.23
Dermis	0.002	0.45
Subcutaneous tissue	0.018	0.19

Table 2.1 Thickness and thermal conductivity values for different skin layers [19]

2.2.5 Skin surface temperature readings with varying ambient temperature

Winslow CEA et al. [28] presented and discussed the variation of skin surface temperature with changing ambient temperature as seen in Table 2.2. There is variation in T_s corresponding to T_a within a certain range as in this case, this range lies in between 29.2℃ to 35.1℃. It may be noted that skin surface temperature shall always increase till a certain limit of ambient temperature is reached as in this case it may be seen that when T_a is 35.5℃, the value of T_s is 35.1℃. At 35.5℃, it is clear that with the increase in ambient temperature, there is a reduction in skin surface temperature (35.1℃).

Ambient temperature, T_a (℃)	Skin surface temperature, T_s (℃)
6.8	29.2
8.7	28.5
11.6	29.7
13.6	30.4

16.1	30.3
19	31
22.6	30.9
24.5	34.7
27.6	33.4
31.5	34.6
33.3	34.2
35.5	35.1

Table 2.2 Skin surface temperature values at different ambient temperature [28]

Cohen Myron L. [30] presented the constructive use of various techniques for the detection and interpretation of temperature patterns either for surface or subsurface or for both depending upon various properties such as thermal properties of the tissue which is to be examined. The author also made comments with respect to the overall thermal balance of the human body through various heat transfer modes. Convection, conduction and radiation are three such modes to support this phenomenon. The author concluded that the thermal properties of human skin suffer variation as the site of measurement is changed. Also, the thermal conductivity, k is dependent on temperature.

Fanian Ferial [31] studied various changes in human skin surface parameters due to the variation in temperature during winter season. Various changes have been observed and discussed in this research work with reference to the skin density and thickness parameter variation. Participation of 8 healthy subjects aged 36-55 years lead to the success of this research work and no major variation in viscoelasticity was observed at the end.

2.2.6 Hemodynamic characteristics

Azran Azhim [32] studied that arterial blood pressure ranges between a maximum and a minimum value which is also termed as systolic and diastolic arterial blood pressure values. These two values helps to generate the required pressure called the pulse pressure which is the difference between the systolic and diastolic values. Waveforms of pulse pressure depend on arterial network characteristics. There is variation in amplitude and shape depending on the arterial network. The mean data of various hemodynamic characteristics for both men and women are shown in Table 2.3.

Hemodynamic characteristics	Men (n=30) Mean Data ± SD	Women(n=20) Mean Data ± SD
D	20 ± 3	22 ± 4
S1	120 ± 21	106 ± 14
S2	55 ± 11	61 ± 10
I	29 ± 6	33 ± 9
D	45± 6	45 ± 9

Table 2.3 Hemodynamic characteristics in men and women [32]

CHAPTER 3

SYSTEM AND SOFTWARE IMPLEMENTATION

3.1 SYSTEM IMPLEMENTATION

A mathematical bio-heat transfer model has been constructed with the purpose to study and validate this proposed research work. Various mathematical equations obtained either from literature survey or the derived ones contribute together in the formation of this mathematical model. The implementation of the physical phenomenon termed as heat transfer in accordance with the various modes of heat transfer to this mathematical model is a complete new task. Various mathematical equations obtained in this study are programmed, simulated and validated by the use of a software tool named MATLAB. For this purpose, all the mathematical equations are scripted and simulated in this software tool to validate the model by obtaining different graphical plots as the final outcomes. The readings obtained for different physical parameters are stored in excel files. The excel files are imported into MATLAB as it has the provision of importing data in various forms. Various plots are available for the purpose of plotting this obtained data in order to simulate and validate this model.

3.1.1 Introduction

MATLAB is a mathematical tool consisting of words matrix and laboratory. The mode of programming is in the form of script files which are stored as ".m" file. Simple mathematical scripts are used for programming all the mathematical equations in the derived mathematical model. The representation of such files can be in the form of "filename.m" when stored as final script file. To simulate this script file, "Run" command is used in MATLAB [37] by pressing the key "F5". The mathematical results obtained for various parameters can be stored in excel file with the representation "filename.xlsx". These excel readings are then imported as a data in MATLAB for the purpose of plotting. Command used for plotting purpose is "plot". For all the required parameters, different plots are generated using this mathematical data. The provision of "xlabel" and "ylabel" allows the user to address the x-axis and y-axis in the obtained plots. Parameters studied and discussed in this work are ambient temperature, skin surface temperature, blood temperature, blood viscosity and systolic and diastolic pressure. All these discussed parameters have an effect on their final values and are thus said to be inter related with each other. Simulations by obtaining different graphical plots and validation by matching the obtained results with the theoretical mathematical model results (expected results) prove this study to be approaching in the right direction.

3.2 Methodology

Overall thermal balance of the human body is determined by the thermal properties of the human skin. Radiation, conduction and convection are the three heat transfer techniques to obtain the required thermal balance. For example, conduction or conductive heat transfer occur through brachial artery and different skin layers i.e. subcutaneous tissue-dermis-epidermis as there is a particular value of thermal conductivity of the artery and the skin layers. Convection or convective heat transfer occur due to blood flow as blood has appropriate values for thermal conductivity (k_b) and convective heat transfer coefficient (h_b). Convection also takes place at human skin surface as skin is in direct contact with the air. Radiative heat transfer occurs at the skin surface as heat may be absorbed or reflected by the skin, or it may get transmitted through different skin layers. Skin surface temperature (Ts) of the human body is an important physiological parameter reflecting the heat transfer between the human body and its thermal environment. Primary layers of skin are epidermis, dermis and the subcutaneous tissue. These three layers differ in physiological characteristics [19]. For example, epidermis is a very thin layer (80 μm on average) composed mainly of cells. The dermis is a thicker layer (2000 μm on average) composed of more fibers as compared to the epidermis. The thickness of the subcutaneous tissue is about 18000 μm. The three layers also differ in terms of thermal conductivity (k). The different parameters employed and their values are listed in Table 3.1.

Skin layer	Thickness, δ (m)	Thermal conductivity, k W/(m k)
Epidermis	0.000008	0.23
Dermis	0.002	0.45
Subcutaneous tissue	0.018	0.19

Table 3.1 Thickness and thermal conductivity values for different skin layers [19]

3.2.1 Calculation for body and skin surface area

The study of DuBois D. et al. [10] presented a mathematical result which says that the body surface area of humans may be expressed by the equation:

$$BSA\ (m^2) = (wt^{0.425} \times ht^{0.725}) \times 0.007184 \qquad (1)$$

where weight is in kilograms and height is in centimeters. As the weight and height varies, BSA also varies from person to person. According to the work presented by Bloomfield Aaron et al. [11] in which they constructed various low cost tactors with the purpose of finding vibrotactile feedback across the whole human arm and discussed that the average skin surface area (A_s) of human arm is about 9% of the body surface area and can be expressed by equation:

$$A_s = (0.09 \times BSA) \qquad (2)$$

3.2.2 Obtaining overall heat transfer coefficient of skin

Epidermis, dermis and subcutaneous, the three layers of skin have different thickness and thermal conductivity values which are required to obtain the overall heat transfer coefficient of skin as shown in equation (3). Overall heat transfer coefficient of skin can be calculated if the values of thicknesses of various skin layers are known along with the values of their thermal conductivity. This is an important factor in maintaining the overall thermal balance of the human body as skin play a significant role in protection and maintenance from varying environmental conditions and the value of overall heat transfer coefficient of skin is represented as

$$\frac{1}{h_s} = \frac{1}{\frac{(k_e \times A_e)}{\delta_e}} + \frac{1}{\frac{(k_d \times A_d)}{\delta_d}} + \frac{1}{\frac{(k_s \times A_s)}{\delta_s}} \quad (3)$$

3.2.3 Calculating heat transfer coefficient of artery

Arterial parameters play an important role in heat transfer, thus maintaining the thermal balance inside. In this case, the required arterial parameters are the thickness and the area of artery. Artery is in direct contact with the blood, thus the heat transfer coefficient of artery and the convective heat transfer coefficient of blood play a significant role to aid heat transfer related to artery and blood. Heat transfer coefficient of artery is obtained from thermal conductivity, thickness and area of artery and is represented by the equation:

$$\frac{1}{h_a} = \frac{1}{\frac{(k_a \times A_a)}{\delta_a}} \quad (4)$$

3.2.4 Determining overall heat transfer coefficient

Various skin layers, arterial and blood parameters contribute together in obtaining the overall heat transfer coefficient. To achieve the overall thermal balance, values of heat transfer coefficient of artery, overall heat transfer coefficient of skin and blood parameters are required to find U which is expressed by equation (5). The values assigned to various parameters of equation (5) are shown in Table 3.2.

$$\frac{1}{U} = \frac{1}{(h_b \times A_a)} + \frac{\ln\left(\frac{r_0}{r_i}\right)}{(2 \times \pi \times k_b \times l)} + \frac{1}{h_a} + \frac{1}{(h_s \times A_s)} + \frac{1}{(h_c \times A_s)} + \frac{1}{(h_r \times A_s)} + \frac{1}{(h_{air} \times A_s)} \quad (5)$$

Parameter	Value	Reference
K_b	0.549 W/(m k)	25
L	0.2222 m	12
K_a	0.476 W/(mk)	25
δ_a	0.0005 m	27
h_c	3.4 W/(m^2k)	24
h_r	4.8 W/(m^2k)	24
h_{air}	3.95 W/(m^2k)	24

Table 3.2 Values assigned to parameters in equation (5)

3.2.5 Blood Viscosity calculation

Environmental changes may cause change in ambient temperature which may affect blood viscosity through temperature change influence on haematocrit level. Equation [21] suggested by Watanabe that correlates ambient temperature (°F) with haematocrit level is

$$Hct = -0.106\ t + 52.167 \qquad (6)$$

Human blood is often modeled as suspended particles and this suspended fluid is plasma. The plasma viscosity depends on ambient temperature (°C) and is expressed by the equation:

$$vis_{plasma} = vis_{37}\ \exp\ [\beta\ (37\text{-}Ta)] \qquad (7)$$

where, vis_{37} is the plasma viscosity at ambient temperature 37°C (1.4 cp) and β is the temperature coefficient (0.021°C^{-1}) [22]. Haematocrit level influence blood viscosity, thus affect mean arterial pressure (MAP). Blood viscosity varies due to the large differences in haematocrit. To model blood viscosity, a theoretical model for spherical particles is given by Vand [20] and for blood, it can be expressed as

$$vis_{blood} = vis_{plasma} \exp\left(\frac{4.1 \times Hct}{1.64 - Hct}\right) \tag{8}$$

where, vis_{blood} is blood viscosity, vis_{plasma} is plasma viscosity and Hct is the haematocrit percentage [22].

3.2.6 Dimensional analysis of artery

Dimensions of brachial artery differ in both men and women. The internal diameter varies from 4.1 to 4.8 mm for men and from 3.5 to 4.3 mm for women [26]. Therefore, average arterial diameter for men is 4.45 mm and for women is 3.9 mm. As listed in Table 3.3, the radius and area of artery also differs in both men and women.

Parameter	Men	Women
Inner Diameter	4.45 mm	3.9 mm
r_i	0.002225 m	0.00195 m
δ_a	0.0005 m [27]	0.0005 m [27]
r_0	0.002725 m	0.00245 m
A_a	0.003106375 m^2	0.002722441 m^2

Table 3.3 Arterial parameter values in men and women

3.2.7 Determination of Blood temperature

Overall heat transfer from ambient conditions outside the arm to blood within the artery through various skin layers and vice-versa may be expressed by the equation:

$$(m \times C_p)\ \Delta t_1 = (U \times A_a)\ \Delta t_2 \tag{9}$$

Parameter	Value
C_p	0.94 [23]
Δt_1	T_b - T_s
Δt_2	T_s – Ta

Table 3.4 Values assigned to parameters in equation (9)

By solving equations (5) and (9), we get equation (10) representing the final output as blood temperature (T_b) depending on the skin temperature (T_s), ambient temperature (Ta), overall heat transfer coefficient (U) and mass flow rate (m).

$$T_b = \frac{1}{(m \times C_p)} \{T_s[(U \times A_a) + (m \times C_p)] - [T_a(U \times A_a)]\} \tag{10}$$

3.2.8 Obtaining Blood Pressure drop

This mathematical equation represents direct relationships between ambient temperature-blood temperature and skin temperature-blood temperature depending on the overall heat transfer coefficient. Blood pressure drop depends on blood viscosity, length of artery, blood flow rate and radius of artery. As there is variation in temperature, the blood viscosity also varies which gives the value of pressure drop. Blood pressure drop in the artery may be calculated from Hagen-Poiseuille equation [29] which can be expressed as

$$P_d = \frac{8 \times vis_{blood} \times l \times Q}{\pi \times {r_i}^4} \quad (11)$$

3.3 Algorithm

Step 1: Body surface area in equation (1) is obtained by entering the values of height and weight of a person.

Step 2: Equation (2) gives the value of skin surface area of arm from body surface area.

Step 3: Overall heat transfer coefficient of skin as expressed in equation (3) is obtained from thermal conductivity, surface area and thickness of each layer of skin.

Step 4: Equation (4) provide heat transfer coefficient of artery using thermal conductivity, surface area and the thickness of artery.

Step 5: The value of overall heat transfer coefficient is calculated as expressed in equation (5).

Step 6: Haematocrit percentage depending on temperature can be calculated from equation (6).

Step 7: Viscosity of blood is obtained from plasma viscosity and haematocrit level as represented in equation (8).

Step 8: The value of blood temperature is calculated as expressed in equation (10).

Step 9: Pressure drop during systole and diastole is obtained from equation (11).

Body Surface Area, BSA [m^2]

↓

Skin Surface Area, A_s [m^2]

↓

Heat transfer coefficient of skin, h_s [W/ (m^2k)]

↓

Heat transfer coefficient of artery, h_a [W/ (m^2k)]

↓

Overall heat transfer coefficient, U [W/ (m^2k)]

↓

Plasma viscosity, vis_{plasma} [Ns/m^2]

↓

Blood viscosity, vis_{blood} [Ns/m^2]

↓

Blood temperature, T_b [°C]

↓

Blood pressure drop, P_d [N/m^2]

3.4 Software Implementation

3.4.1 Enter the height

Enter the height of a person in centimeters which is the first step in the implementation of software. The value of height (input) to be entered by the user must be in centimeters.

3.4.2 Enter the weight

Enter the weight of a person in kilograms which is the second step in the implementation of software. The value of weight (input) to be entered by the user must be in kilograms.

3.4.3 Enter ambient temperature

Enter the value of ambient temperature, T_a in degree celsius as the third step in the implementation of software. The value of the varying ambient temperature (input) to be entered by the user must be in°C.

3.4.4 Enter skin surface temperature

Enter the skin surface temperature, T_s which may vary from person to person in degree celcius which is the fourth and the last input step in the implementation of software. The value of T_s (input) to be entered by the user must be in°C.

3.4.5 Body Surface Area (BSA) as output

The software gives BSA (m^2) as output with the help of the coded mathematical equation (1) for body surface area. This requires height (cm) and weight (kg) of person as input.

3.4.6 Skin surface area (A_s)

The software gives A_s (m^2) as output with the help of the coded mathematical equation (2) for skin surface area. This requires BSA (m^2) of person as an input. The value for A_s is further required for the calculation of heat transfer coefficient of skin.

3.4.7 Overall heat transfer coefficient of skin, h_s

Next step of the software provides h_s [W/ (m^2k)] as output with the help of the coded mathematical equation (3) for heat transfer coefficient of skin. This requires A_s (m^2) of person as input. The value for h_s is required for the mathematical calculation of overall heat transfer coefficient (U).

3.4.8 Heat transfer coefficient of artery, h_a

This step of the software evaluates h_a [W/ (m^2k)] as output with the help of the coded mathematical equation (4) for heat transfer coefficient of artery. The value for h_a is required to obtain the value of overall heat transfer coefficient (U).

3.4.9 Overall heat transfer coefficient, U

In this step, the software calculates U [W/ (m^2k)] as output with the help of the coded mathematical equation (5) for overall heat transfer coefficient. This requires h_s and h_a of a particular person as inputs. The value for U (overall heat transfer coefficient) is required for the calculation of blood temperature (T_b).

3.4.10 Haematocrit percentage and blood viscosity

Haematocrit percentage depending on ambient temperature can be calculated from equation (6). In addition to this, viscosity of blood is obtained from haematocrit level (equation 6) and plasma viscosity (equation 7) as represented in equation (8).

3.4.11 Calculation for blood temperature, T_b

The value of blood temperature, T_b in ℃ is calculated in this step by coding of mathematical equation (10). This step requires the value of overall heat transfer coefficient (U), ambient temperature (T_a) and skin surface temperature (T_s).

3.4.12 Calculating blood pressure drop, P_d

Depending on the variation in blood viscosity as obtained in equation (8), the value of pressure drop (systolic or diastolic) in mmHg is obtained in this programmed step of equation (11).

CHAPTER 4

RESULTS AND DISCUSSION

For healthy individuals with age 27±4 years, height 170±5 cm and weight 73±5 kg (means±SD), various results are presented and discussed. As the height and weight increases, U also increases as represented in Table 4.1.

Age (years)	Height (cm)	Weight (kg)	Overall heat transfer coefficient, U
30	165	68	0.17757
24	170.6	73	0.18623
26	175	78	0.19394

Table 4.1 U increases with increasing height and weight

Results presented and discussed here are for a healthy individual (men) with height 170.6 cm and weight 73 kg. As the ambient temperature increases, the skin surface temperature also increases [28] but after a particular temperature limit, there is decrease in mean skin surface temperature with increase in ambient temperature [18]. Various readings of T_s at different ambient temperatures are seen in Table 4.2. Results are shown in Fig.4.1 for various values of T_a and T_s.

Ambient temperature, T_a (°C)	Skin surface temperature, T_s (°C)
6.8	29.2
8.7	28.5
11.6	29.7
13.6	30.4
16.1	30.3
19	31
22.6	30.9
24.5	34.7
27.6	33.4
31.5	34.6
33.3	34.2
33.5	35.1

Table 4.2 Variation of skin surface temperature with ambient temperature

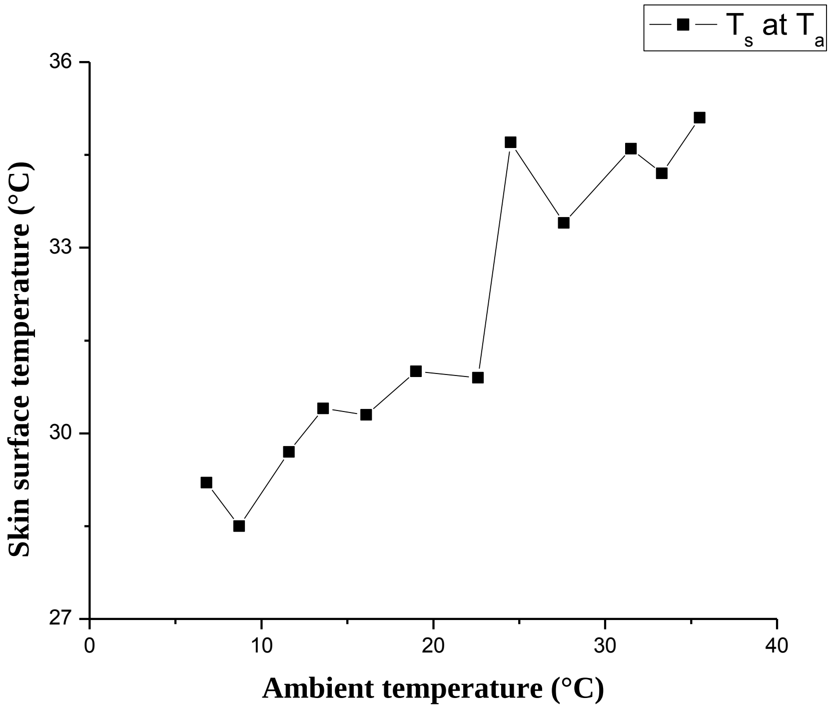

Fig. 4.1 Variation of T_s with T_a

Figures 4.2 and 4.3 represent the variation of blood temperature with ambient and skin surface temperature. From equation (10), it is clear that with the variation of T_a and T_s, the blood temperature T_b also varies depending on overall heat transfer coefficient, U.

Blood temperature variations at different ambient temperatures are seen in Table 4.3. Blood temperature variations at different skin surface temperatures are seen in Table 4.4.

Ambient temperature, T_a (℃)	Blood temperature, T_b (℃)
6.8	40.162
8.7	38.2735
11.6	38.7482
13.6	38.8865

16.1	37.6152
19	37.348
22.6	35.5803
24.5	40.3534
27.6	37.0318
31.5	37.052
33.3	35.6476
33.5	35.9886

Table 4.3 Blood temperature readings at different ambient temperature

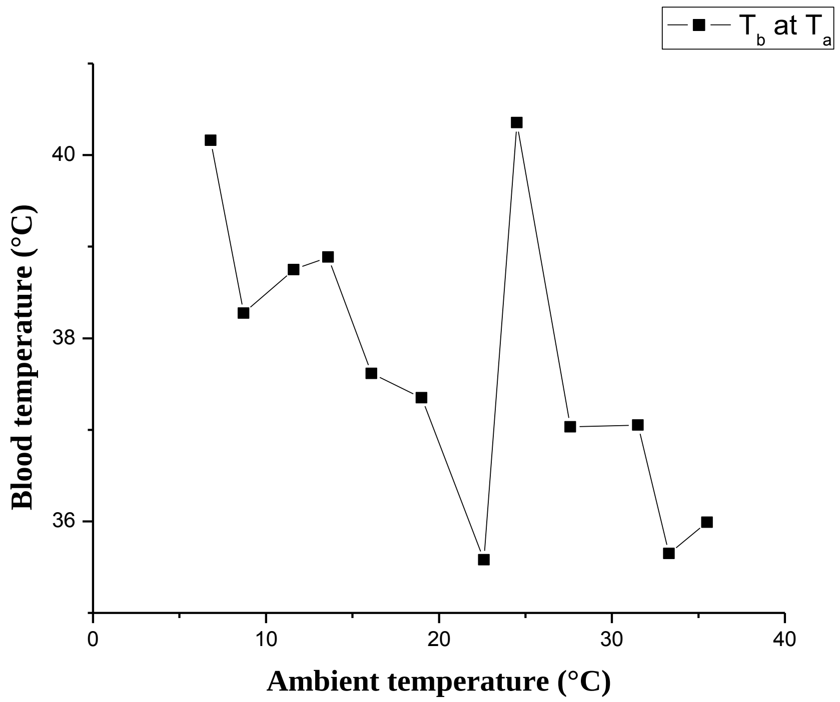

Fig. 4.2 Variation of T_b with T_a

Skin surface temperature, Ts (℃)	Blood temperature, T_b (℃)
29.2	40.162
28.5	38.2735
29.7	38.7482
30.4	38.8865
30.3	37.6152
31	37.348
30.9	35.5803
34.7	40.3534
33.4	37.0318
34.6	37.052
34.2	35.6476
35.1	35.9886

Table 4.4 Blood temperature readings at different values of skin surface temperature

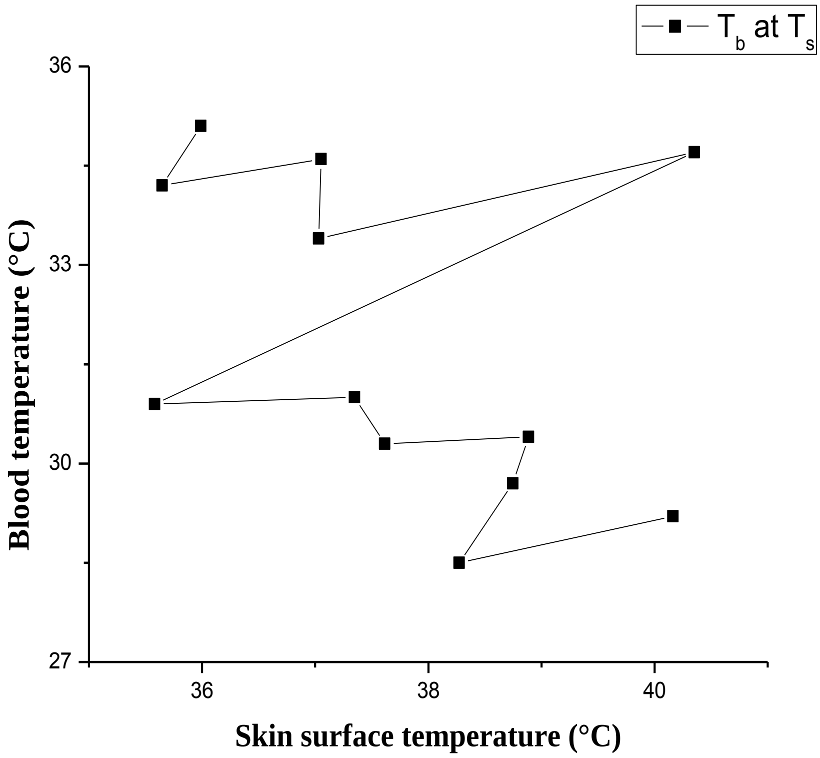

Fig. 4.3 Variation of T_b with T_s

Equation (7) represents the value of plasma viscosity depending on ambient temperature T_a which further varies the blood viscosity as shown in equation (8). By solving equations (7) and (8), it is said that ambient temperature certainly has an effect on viscosity of blood. Fig.4.4 shows decrease in viscosity of blood with increasing ambient temperature T_a. Table 4.5 shows various values of blood viscosity variation in accordance with the variation in ambient temperature.

Ambient temperature, T_a (°C)	Blood viscosity, vis_{blood} (Ns/m^2)
6.8	0.014031
8.7	0.013243
11.6	0.012127
13.6	0.011415

16.1	0.010584
19	0.009699
22.6	0.008705
24.5	0.008224
27.6	0.007496
31.5	0.006674
33.3	0.006327
33.5	0.005927

Table 4.5 Blood viscosity readings at different ambient temperature

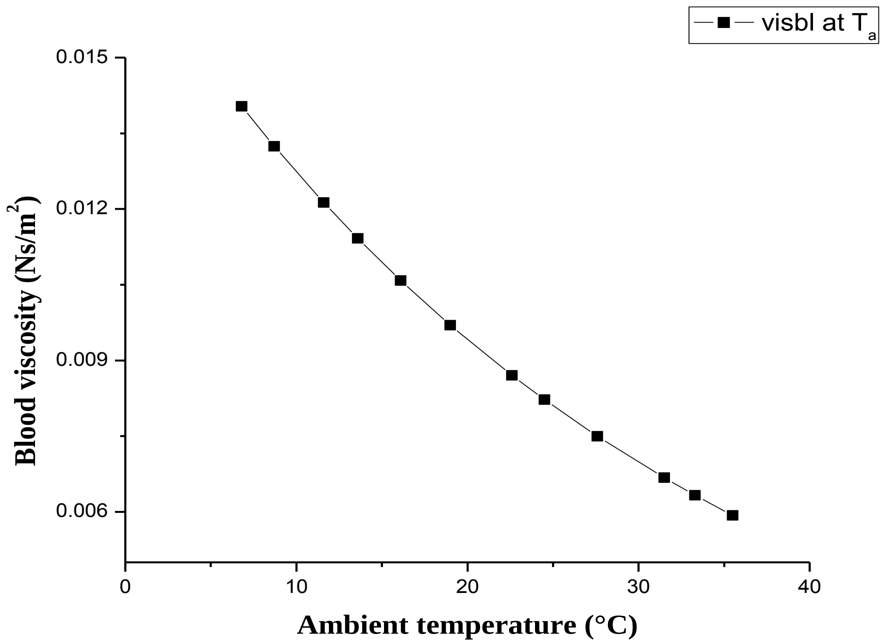

Fig. 4.4 Decrease in blood viscosity with increasing T_a

With the variation in ambient temperature, there is change in blood temperature as shown in Fig.4.2. Change in T_b results in blood viscosity variation as represented in Fig.4.5. As the viscosity of blood increases, there is increase in systolic and diastolic pressure drop as expressed in equation (11) and the results are shown in Fig. 4.6. Table 4.6 shows various values of blood viscosity variation in accordance with the variation in blood temperature. Blood pressure drop variation in accordance with the blood viscosity and their different readings are shown in Tables 4.7.

Blood temperature, T_b (°C)	Blood viscosity, Vis_{blood} (Ns/m^2)
40.162	0.014031
38.2735	0.013243
38.7482	0.012127
38.8865	0.011415
37.6152	0.010584
37.348	0.009699
35.5803	0.008705
40.3534	0.008224
37.0318	0.007496
37.052	0.006674
35.6476	0.006327
35.9886	0.005927

Table 4.6 Different values of blood viscosity at different blood temperature readings

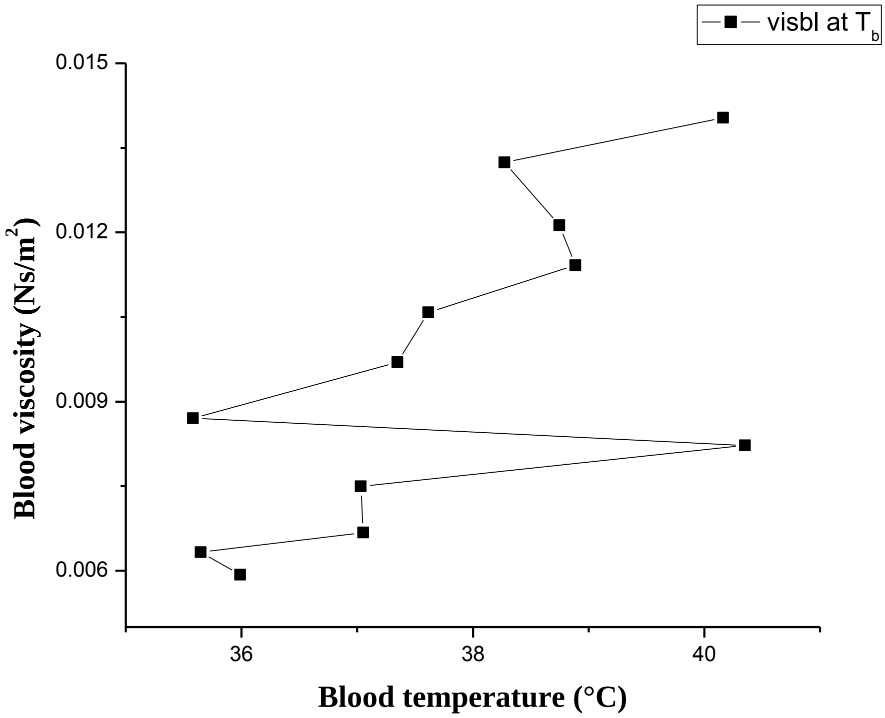

Fig. 4.5 Blood viscosity decreases as T_b increases

Blood viscosity, Vis_{blood} (Ns/m^2)	Systolic pressure drop (mmHg)	Diastolic pressure drop (mmHg)
0.014031	6.547	0.90322
0.013243	6.1779	0.8523
0.012127	5.6555	0.78023
0.011415	5.322	0.73421
0.010584	4.9334	0.68061
0.009699	4.5191	0.62345
0.008705	4.0543	0.55932

0.008224	3.8291	0.52826
0.007496	3.489	0.48135
0.006674	3.105	0.42836
0.006327	2.9427	0.40597
0.005927	2.7561	0.38023

Table 4.7 Systolic and diastolic pressure drop variation with varying blood viscosity

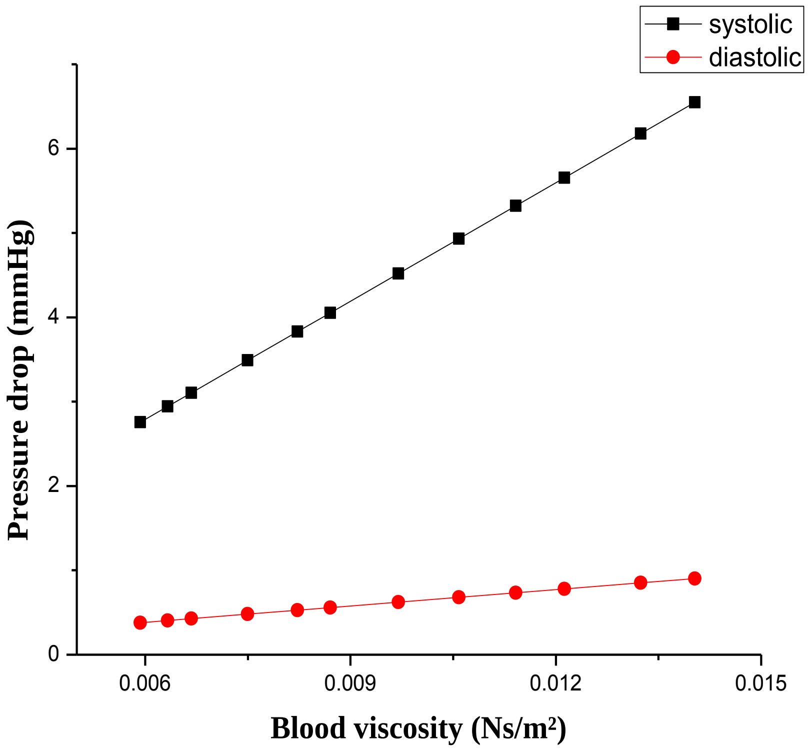

Fig.4.6 Systolic and diastolic pressure drop increases with increasing blood viscosity

With the variation in ambient temperature, the systolic and diastolic pressure drop also varies as change in T_a results in change of T_b which further changes viscosity of blood. Hence it can be said that there is a relation between the blood pressure drop within the artery and the ambient temperature with their results represented graphically in Fig. 4.7.Various pressure drop values at different T_a are represented in Table 4.8.

Ambient temperature, T_a (℃)	Systolic pressure drop (mmHg)	Diastolic pressure drop (mmHg)
6.8	6.547	0.90322
8.7	6.1779	0.8523
11.6	5.6555	0.78023
13.6	5.322	0.73421
16.1	4.9334	0.68061
19	4.5191	0.62345
22.6	4.0543	0.55932
24.5	3.8291	0.52826
27.6	3.489	0.48135
31.5	3.105	0.42836
33.3	2.9427	0.40597
35.5	2.7561	0.38023

Table 4.8 Readings of systolic pressure drop at different ambient temperature

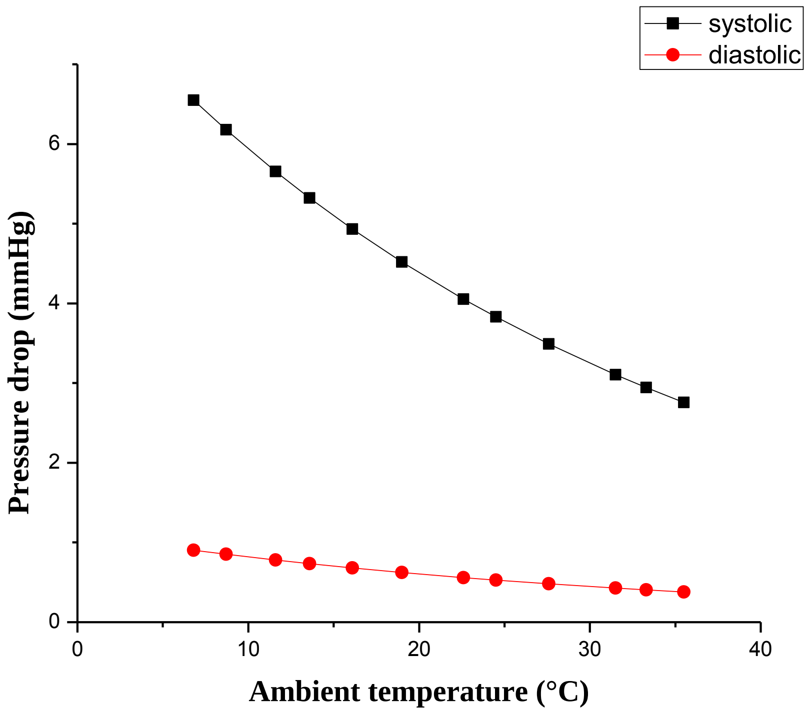

Fig. 4.7 Systolic and diastolic pressure drop decreases with increasing T_a

Results presented and discussed below are for both men and women with same height 170.6 cm and weight 73 kg. As there is increase in ambient temperature (T_a), there is increase in skin surface temperature (T_s) [29] but after reaching the threshold temperature limit (when T_s stop increasing), the mean skin surface temperature (T_{skin}) decreases with further increase in ambient temperature [18]. From equation (10), it is very clear that there is variation in T_b along with the variation of T_a and $T_{skin.}$ Variation of blood temperature with ambient temperature is shown in Table 4.9. Variation of blood temperature with skin surface temperature is shown in Table 4.10. For the variation of T_b along with the variation of T_a, results are plotted in Fig.4.8 and for the variation of T_b along with the variation of $T_{s,}$ results are plotted in Fig.4.9 and hence, a comparison is made for this analysis of different blood temperatures. From both the figures 4.8 and 4.9, it is observed that the blood temperature in men always suffers a slight increase comparatively to that in case of women.

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Ambient temperature, T_a (℃)	Blood temperature in men, M_{Tb} (℃)	Blood temperature in women, W_{Tb} (℃)
6.8	40.162	38.3135
8.7	38.2735	36.4804
11.6	38.7482	36.893
13.6	38.8865	36.9967
16.1	37.6152	35.7453
19	37.348	33.4485
22.6	35.5803	33.7068
24.5	40.3534	38.244
27.6	37.0318	35.0237
31.5	37.052	34.9874
33.3	35.6476	33.619
35.5	35.9886	33.9138

Table 4.9 Blood temperature variation with ambient temperature

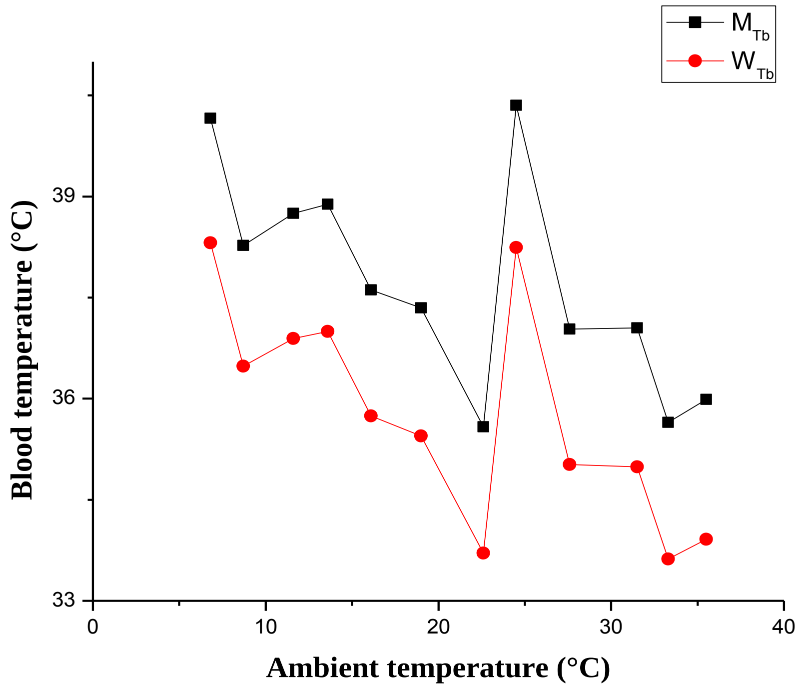

Fig. 4.8 Variation of T_{bl} with T_a

Skin surface temperature, T_s (°C)	Blood temperature in men, M_{Tb} (°C)	Blood temperature in women, W_{Tb} (°C)
29.2	40.162	38.3135
28.5	38.2735	36.4804
29.7	38.7482	36.893
30.4	38.8865	36.9967
30.3	37.6152	35.7453
31	37.348	33.4485

30.9	35.5803	33.7068
34.7	40.3534	38.244
33.4	37.0318	35.0237
34.6	37.052	34.9874
34.2	35.6476	33.619
35.1	35.9886	33.9138

Table 4.10 Blood temperature variation with skin surface temperature

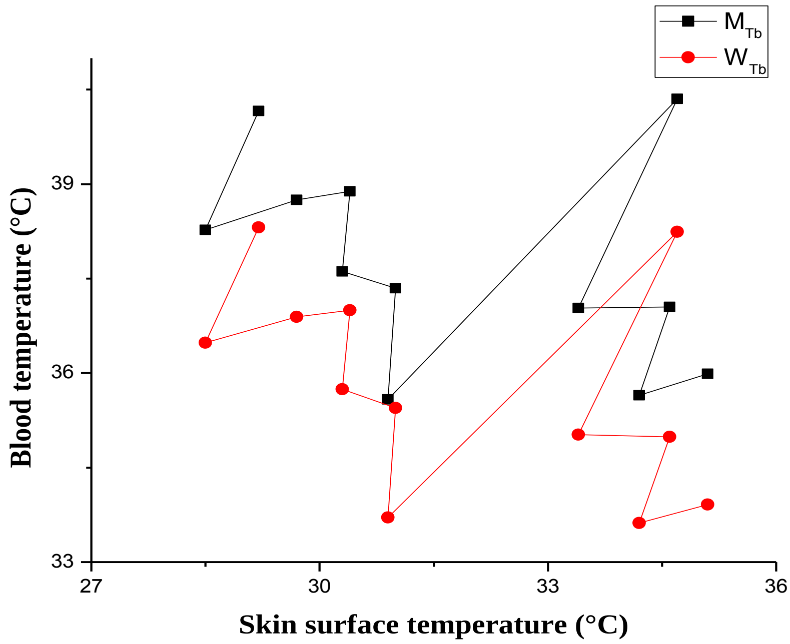

Fig. 4.9 Variation of T_{bl} with T_{skin}

Due to the variation in ambient temperature (T_a), the blood viscosity also varies. This statement proves to be true as the mathematical result by solving equations (7) and (8) which says that as the ambient temperature varies, plasma viscosity also varies (equation 7) which further varies blood viscosity (equation 8). This can be represented graphically as seen in Fig.4.10. Hence, it may be said that viscosity of blood (vis_{bl}) suffers a decrease with increasing ambient temperature (T_a) as seen in Table 4.11. On comparison of both the obtained results for men and women, it is observed that readings of blood viscosity for women are slightly less as compared to those with the blood viscosity values for men.

Ambient temperature, T_a (°C)	Blood viscosity in men, M_{Tb} (Ns/m^2)	Blood viscosity in women, W_{Tb} (Ns/m^2)
6.8	0.014031	0.010107
8.7	0.013243	0.009575
11.6	0.012127	0.008816
13.6	0.011415	0.008329
16.1	0.010584	0.007759
19	0.009699	0.007147
22.6	0.008705	0.006456
24.5	0.008224	0.006119
27.6	0.007496	0.005608
31.5	0.006674	0.005026
33.3	0.006327	0.004779
35.5	0.005927	0.004494

Table 4.11 Change in blood viscosity with changing ambient temperature

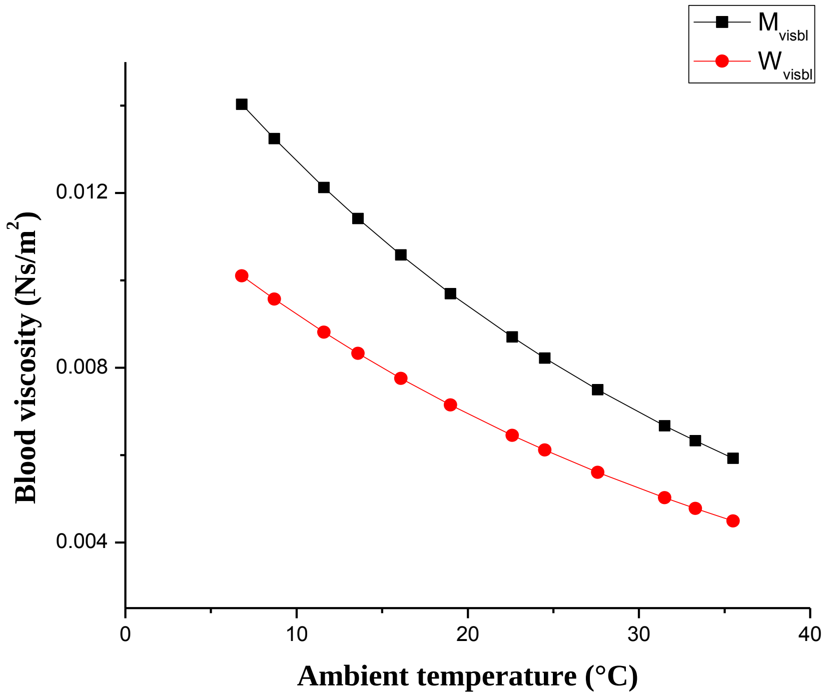

Fig. 4.10 Change in blood viscosity with changing T_a

The blood pressure drop within the brachial artery decreases with decreasing blood viscosity and vice-versa. This can be said with respect to equation (11) as it is clear that blood viscosity variation causes a change in readings of blood pressure drop. From Fig. 4.10, it is clear that blood viscosity decreases with increasing ambient temperature. This decrease in blood viscosity act as an input to equation (11) which results in decrease of blood pressure drop. The systolic blood pressure drop decreases with increasing T_a as seen in Table 4.12 and represented in Fig. 4.11. It is observed that for men, the values of systolic pressure drop are slightly higher than those in case of systolic pressure drop values for women. On the contrary, the diastolic pressure drop in case of women has higher values as compared to those in case of men as seen in Table 4.13 and represented in Fig. 4.12.

Ambient temperature, T_a (℃)	Systolic pressure drop in men, M_{sys} (mmHg)	Systolic pressure drop in women, W_{sys} (mmHg)
6.8	6.547	5.9356
8.7	6.1779	5.6011
11.6	5.6555	5.1276
13.6	5.322	4.8253
16.1	4.9334	4.4732
19	4.5191	4.0977
22.6	4.0543	3.6763
24.5	3.8291	3.4723
27.6	3.489	3.164
31.5	3.105	2.8158
33.3	2.9427	2.6687
35.5	2.7561	2.4996

Table 4.12 Systolic pressure drop variation with ambient temperature

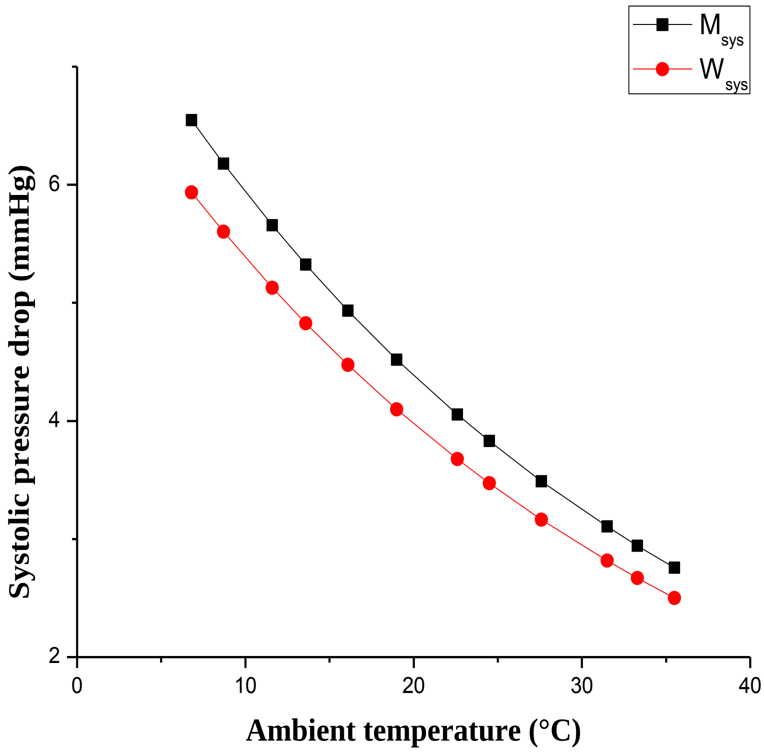

Fig. 4.11 Systolic pressure drop variation with T_a

Ambient temperature, T_a (°C)	Diastolic pressure drop in men, M_{dia} (mmHg)	Diastolic pressure drop in women, W_{dia} (mmHg)
6.8	0.90322	0.95539
8.7	0.8523	0.90155
11.6	0.78023	0.82534
13.6	0.73421	0.77669
16.1	0.68061	0.72

19	0.62345	0.65956
22.6	0.55932	0.59174
24.5	0.5286	0.55889
27.6	0.48135	0.50928
31.5	0.42836	0.45324
33.3	0.40597	0.42955
35.5	0.38023	0.40233

Table 4.13 Diastolic pressure drop variation with ambient temperature

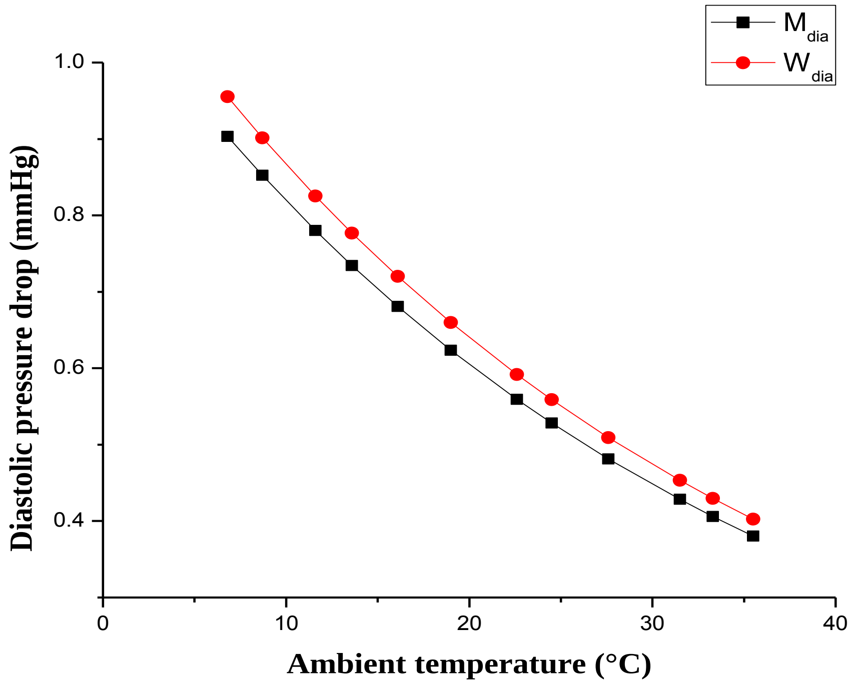

Fig. 4.12 Diastolic pressure drop variation with T_a

Blood flows within the artery at a certain flow rate which is an important factor in observing the blood pressure drop throughout the arterial length. From the analysis made above, it can be said that heat transfer due to ambient temperature variation certainly affects blood pressure drop. The systolic and diastolic blood pressure drop values in both men and women due to the variation in ambient temperature, blood temperature and blood viscosity are observed and represented in Table 4.14 below. This analysis helps to infer about the complete functioning of the human heart and its cardiac cycle.

Ambient temperature, Ta (°C)	Skin surface temperature, T_s (°C)	Blood temperature, T_b (°C)		Blood viscosity (Ns/m^2)		Systolic pressure drop (mmHg)		Diastolic pressure drop (mmHg)	
		Men	Women	Men	Women	Men	Women	Men	Women
6.8	29.2	40.162	38.3135	0.014031	0.010107	6.547	5.9356	0.90322	0.95539
8.7	28.5	38.2735	36.4804	0.013243	0.009575	6.1779	5.6011	0.8523	0.90155
11.6	29.7	38.7482	36.893	0.012127	0.008816	5.6555	5.1276	0.78023	0.82534
13.6	30.4	38.8865	36.9967	0.011415	0.008329	5.322	4.8253	0.73421	0.77669
16.1	30.3	37.6152	35.7453	0.010584	0.007759	4.9334	4.4732	0.68061	0.72
19	31	37.348	35.4485	0.009699	0.007147	4.5191	4.0977	0.62345	0.65956
22.6	30.9	35.5803	33.7068	0.008705	0.006456	4.0543	3.6763	0.55932	0.59174
24.5	34.7	40.3534	38.244	0.008224	0.006119	3.8291	3.4723	0.52826	0.55889
27.6	33.4	37.0318	35.0237	0.007496	0.005608	3.489	3.164	0.48135	0.50928
31.5	34.6	37.052	34.9874	0.006674	0.005026	3.105	2.8158	0.42836	0.45324
33.3	34.2	35.6476	33.619	0.006327	0.004779	2.9427	2.6687	0.40597	0.42955
35.5	35.1	35.9886	33.9138	0.005927	0.004494	2.7561	2.4996	0.38023	0.40233

Table 4.14 Variation in blood temperature, blood viscosity and blood pressure drop with ambient temperature variation

CHAPTER 5

CONCLUSION AND FUTRE SCOPE

In the introduction of this dissertation, I expressed the hope that in this work, the studied and implemented work could be a ‘first step’ towards the improvement of the blood pressure measuring instruments. In the final chapter, I will conclude by providing a description to the progress made towards the set goal in the beginning. I will also make suggestion towards some future research directions that might be helpful in providing the next steps for further improvement.

5.1 CONCLUSION

Heat transfer modes play a significant role in overall thermal balance maintenance of human body by regulating the blood temperature. Change in climatic conditions results in variation of ambient temperature. Skin surface temperature which varies with the ambient temperature also helps in maintaining the overall thermal balance depending on h_a, h_r and h_c. Different skin layers i.e. epidermis, dermis and subcutaneous tissue also play a vital role in transfer of heat depending on the values of their thermal conductivity represented as k_e, k_d and k_s. Thickness of each skin layer δ_e, δ_d and δ_s is also of prime importance while studying the amount of heat transfer for skin. Arterial parameters δ_a and k_a may also be considered in achieving the overall thermal balance and studying the heat transfer between the skin and the artery. Blood flows within the artery at a certain flow rate which is an important factor in studying the blood pressure drop. Relation between ambient temperature and blood temperature is expressed in equation (10) which shows the variation in T_b with increase or decrease in T_a. As T_b changes, there is change in viscosity of blood. Blood pressure drop value for this change in blood viscosity can be obtained from equation (11) which represents the pressure drop for both systolic and diastolic blood pressure. The value of the pressure drop obtained by this method is said to be the blood pressure drop-correction factor (BPD-CF) when considering the effect of ambient temperature variation on blood pressure. This BPD-CF value gets added as a correction factor to the values (systolic and diastolic) represented as final outcomes of the blood pressure measuring instruments. This analysis helps to infer about the functioning of the heart and its cardiac cycle.

5.2 FUTURE SCOPE

The study of ambient temperature effect on blood pressure drop using MATLAB is a new concept and an efficient program. However, the chances of improvement are still there.

1. This work can be extended in order to analyze or to obtain a clear visualization of the concept of blood pressure drop throughout human body considering ambient temperature effect using computational fluid dynamics (CFD).
2. To analyze the effect of contraction and expansion coefficients on blood pressure drop when blood flows from artery to capillary and vice-versa.
3. The effect of gravity on blood pressure drop may also be analyzed.

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