修士　論文

水中における人体の熱的応答に関する研究

Study of Human Thermal Reaction in Water Immersion

１－７５ページ　完

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Even though we spend most of our time in land, more and more people involve in water activities for the purpose of such as doing daily activities (taking hot bath, shower etc) and recreational activities (swimming, scuba diving, snorkeling etc). In addition, for occupational reason, some people need to work in a deep sea water and for the purpose of survival, for instance accidental cold water immersion, a proper understand of human thermal or physiological response while they immerse into water is very important. The physical properties of water are very different from those in air. Accordingly, the environmental stress easily become severe and may even threaten life. On immersion heat exchange between the body and its environment is enhanced. Water has a volumetric specific heat 4000 times greater than that of air, and a conductivity 25 times that of air. Water therefore serves as a gigantic heat sink around the body. As the results, it is equally important to study the human thermal response in aquatic environment.

Various human body models have been developed to simulate human thermoregulation. In a simple model, the human body may be considered as only two concentric cylinders, while in some complex models, the body can be divided into more than 50 major elements and body temperatures are computed at tens of thousands of nodal points on a supercomputer. In most cases, human body models are used to predict physiological responses to thermal condition. However, almost all of those model were done in air environment, there is none developed for water environment.

In this study, a numerical modeling has been developed to simulate the human thermal responses in water immersion. The model is then validated with experimental data of taking a bath only. In general, the model is a basic whole body water immersion for taking a bath, further development can be continue to include other water activities as well.

1.2 OBJECTIVE

Since the understanding of human thermal reaction in aquatic environment is so important, the purpose of this study is to

1. To develop numerical model that simulates the human thermal response in water immersion such as mean skin temperature, core temperature, metabolic heat production and evaporative heat loss. This model to be developed in such a format that this can be used to simulate human thermal response in different environment conditions (such as water temperature, air and humidity temperature etc), and also different part of body immersion (i.e. either whole body immersion with only head out or half body immersion)
2. Carry out experiments that measure skin and oral temperature of human in water immersion. The purpose of doing experiment is to validate the simulation result. The experiment is done in three cases that to validate the simulation results in various criteria for instance, different water temperature conditions, two types of body part of immersion and different subjects.

CHAPTER 2

MATHMATICAL MODELING

2.1 BODY HEAT BANLANCE EQUATION

Since the purpose of the thermoregulatory system of the body is to maintain an essentially constant internal body temperature, it can be assumes that for long exposures to a constant (moderate) thermal environment with a constant metabolic rate a heat balance will exist for the human body, i.e., the heat production will the heat dissipation, and there will be no significant heat storage within the body. The heat balance equation [8] describing the thermal exchange between the body and its environment is

$$H = M - E \pm R \pm C - (\pm W) \qquad \left[W.m^{-2}\right] \qquad (2.1)$$

where H = rate of storage of body heat (+ for net gain)

M = rate of metabolic energy production (always +)

E = rate evaporative heat loss

R = rate of radiant heat exchange (+ for gain)

C = rate of convective heat transfer (+ for gain)

W = rate of work (+ for work against external force)

2.11 Body Temperature – Mean Skin Temperature and Core Temperature

Skin temperature may be measured experimentally by appropriately designed thermocouples. Mean skin temperature T_{sk}, is an average of local values of skin temperature over the body surface. Each weighted by the fraction of the total body surface represented. A useful weighting scale is head (7%), chest (17.5%), back (17.5%), upper arms (7%), forearms (7%), hands (5%), thighs (19%), and legs (20%). In the cold, wide differences in skin temperature over the body surface can be expected, which hinder proper interpretation of T_{sk}.

However, in the water immersion, the skin surface temperature tends to be fairly uniform and thus the weighting factors are less significant in determining T_{sk}.

Skin temperature serve as an significant index of the mode of regulation of body temperature. Values of T_{sk} may also serve as indices of our sensory judgment of heat, cold and pain as well as of the thermal comfort the environment. Table 2.1 outlines the general relationships that may be expected between skin temperature and various physiological and sensory states. It shows that the comfort range skin temperature for human is quite limited i.e. 34-36°C. Human will be in critical condition with small increase (about 6°C) and decrease (18°C) in mean skin temperature.

Table 2.1: Range of Skin Temperature

Temp*	State
0 - 5	No sensation
15	No sensation
32 - 33	Sensation of cold
33 - 34	Comfort Zone
35 - 37	Sensation of warm
35-39	Sensation of heat
39 - 41	Pain
41 - 43	Threshold of burning pain
45	Rapid tissue damage

* in degrees Celcius

The temperature of blood reaching the hypothalamus (T_{core}) is regarded as a major afferent stimulus for the intensity of the effector response of sweating, vasomotor activity and shivering. To estimate T_{core} in humans, measurement sites other than the hypothalamus have frequently been utilized, including the oral cavity, tympanice membrane, pulmonary artery (PA) and right heart (RH), rectum and esophagus. Measurement of T_{core} is important both as an estimate of afferent input in the temperature-control system and as an estimate of the temperature of the blood going to the brain. Table 2.2 outlines the general relationships that may be expected between core temperature and various physiological and sensory states.

Table 2.2: Range of Core Temperature

Temp*	State
28	Muscle failure
30	Loss of body temp. control
33	Loss of consciousness
37	**Normal**
42	Central nervous system breakdown
44	Death

* in degrees Celcius

In contrast to the situation in air, water exposure of a nude person will bring the temperature of the skin close to that of water within minutes. The skin-to-water temperature gradient is affected by water temperature, water movement and people` movements. The core temperature is affected little during the first 5 minutes of immersion, irrespective of water temperature and metabolic rate. A longer exposure will, except in a rather narrow `thermoneutral` range of water temperature, induce a change in core temperature. The rate of this change is dependent on factors including water temperature, and the subject metabolic rate and skinfold thickness. Thus the temperature zone in which man can stay in water without excessive heating or cooling is very narrow compared to air.

2.12 Skin Wettedness

Skin wettedness (w) is defined as the ratio of an equivalent akin area (A_{wet}), which, if covered with water, would produce the observed skin evaporative heat loss (E_{sk}) to the total skin surface area (A_{total}). Evaluating of w will be discussed in the section 3.23.

2.2 METABOLIC HEAT PRODUCTION

The metabolic energy term M in the basic heat balance Equation 1 represents the free energy produced by the transformation of chemical energy during aerobic and anaerobic metabolic activities within an organism.

2.3 EVAPORATIVE HEAT EXCHANGE

Evaporative heat loss in man occurred through respiratory system and skin. Evaporation heat loss through skin can then be further divided into skin diffusion and sweat secretion.

2.31 Evaporation Heat Loss by Skin Diffusion

Water vapor diffusion through the skin is one part of the insensible perspiration, a process not subject to thermoregulatory control. The magnitude of the diffusion per unit area is assumed to be proportional to the difference between the saturated water vapor pressure p_s at skin temperature and the partial vapor pressure of water vapor p_a in the ambient air. The equation [3] for the heat loss by water vapor through skin diffusion is

$$E_{diff} = h_{fg} m A_{total} (p_s - p_a) \quad \text{(kJ/hr)} \qquad (2.2)$$

where E_{diff} = heat loss by vapor diffusion through the skin (Watt)

h_{fg} = heat of vaporization of water (kJ/kg, value from Steam table)

m = permeation coefficient of skin, (6.1×10^{-4} kg/hr m^2 mm Hg, from analysis data of Inouye et al)

p_s = saturated vapor pressure at skin temperature (mmHg)

p_a = vapor pressure in ambient air (mmHg)

By substitute the permeation coefficient of skin into eq.2.2 and convert the unit of kJ/hr into Watt, the evaporative heat loss through skin diffusion can be rewritten as:

$$E_{diff} = 1.6944 \times 10^{-4} h_{fg} A_{total} (p_s - p_a) \qquad \text{(W)} \qquad (2.2a)$$

2.32 Evaporation Heat Loss by Sweat Secretion

The heat loss by the evaporation of sweat secretion on the skin surface is humans` most effective means of survival in the heat. The magnitude of the sweat secretion is a function of the activity level. The amount of heat removed by evaporation of sweat is given by

$$E_{sw} = \lambda A_{total} (M / A_{total} - q_o) \qquad (2.3)$$

According to Eq. (2.3) sweating will not occur for metabolic rates (*M*) lower than q_o (a typical value for humans is 58 W/m^2), Above this value, which corresponds to average sedentary conditions in humans, sweating is an increasing function of thermal exposure. λ is an experimental coefficient relating the amount of heat exchange by sweating to physiological parameters. A typical value of is λ for human is 0.32.

2.33 Evaporation Heat Loss by Latent Respiration

Heat and water vapor are transferred to inspired air by convection and evaporation from the mucosal lining of the respiratory tract. On reaching the alveoli the air is at deep body temperature and saturated with water vapor. As the air moves outward through the respiratory tract some heat is transferred back to the body and water is condensed but the expired air emerging from the nose still contain more heat and water than the inspired air in comfortable environments. Breathing therefore results in a latent heat loss and a dry heat loss from body.

The latent respiration heat loss is a function of the pulmonary ventilation and the difference in water content between expired and inspired air:

$$E_{res} = \dot{V}(W_{ex} - W_a)\lambda \qquad \text{(kcal/hr)} \qquad (2.4)$$

where E_{res} = latent respiration heat loss (kcal/hr)

$\dot{V}$ = pulmonary ventilation

W_{ex} = humidity ratio of the expiration air (kg water/ kg dry air)

W_a = humidity ratio of the inspiration air (kg water/ kg dry air)

λ = heat of vaporization of water (value from steam table)

Pulmonary ventilation is mainly a function of the metabolic rate, through minor differences have been observed between working tasks where arm and leg movements respectively are dominant. The following linear expression has been found as a practical approximation for the mean pulmonary for different type of work:

$$\dot{V} = 0.0060M \qquad (2.5)$$

Although the function of the respiratory tract is quite effective, the condition of the expired air will still depend to a certain degree upon the condition of inspired are. The difference between expired and inspired air can be expressed by the following equation:

$$W_{ex} - W_a = 0.0277 + 0.000065t_a - 0.80W_a \qquad (2.6)$$

$$\cong 0.029 - 0.80W_a \qquad \text{(kg water/kg dry air)}$$

Substituting $W_a = 0.622 \frac{p_a}{P - p_a} \cong 0.00083 p_a$ in Eq. (6) gives

$$W_{ex} - W_a = 0.029 - 0.00066 p_a \quad \text{(kg water/kg dry air)} \qquad (2.6a)$$

Where p_a = the partial pressure if water vapor in inspired air (ambient air) (mmHg)

P = 760 mmHg (sea level barometric pressure)

Substituting the expression for $\dot{V}$ and W_{ex} - W_a in Eq. (4), one obtains the following formula for the latent respiration heat loss:

$$E_{res} = 0.0023 M (44 - p_a) \quad \text{(kcal/hr)} \qquad (2.4a)$$

2.4 HEAT EXCHANGE WITH ATMOSPHERE BY SENISIBLE HEAT

The exchange of sensible heat from skin surface at average temperature T_{sk} is usually accomplished by radiation and convection from the skin surface to the surrounding medium. The heat exchange from the body surface without cloth, at skin temperature is given by

$$Q_{sen} = h(T_{sk} - T_a) \quad (\text{Wm}^{-2}) \qquad (2.7)$$

where h is the combined coefficient for heat transfer by radiation and convection in $W.m^{-2}C^{-1}$ and T_a is the ambient air temperature.

2.5 HEAT EXCHANGE WITH WATER ENVIRONMENT

Heat will either transfer from the human body to water or on the other way round is depend upon the temperature difference between the skin and water temperature. In cold water immersion, heat produced in the body core and the limbs is transport by blood convection and tissue conduction to the skin surface for dissipation. Heat arriving at the skin surface will be dissipated to the colder water by convection at a rate determined by the skin to water temperature (T_w) gradient (T_{sk}- T_w) and the heat transfer coefficient for external convection $h_w(Wm^{-2}C^{-1})$.

$$Q_{water} = h_w \left(T_{sk} - T_w\right) \qquad (Wm^{-2}) \qquad (2.8)$$

This is the only important heat transfer at the skin because in water evaporation of sweat cannot be used as a heat dissipating mechanism and heat loss hue to radiation is negligible.

On the other hand, warm water immersion will result in a negative Q_{water} showing that the heat is transferred from the water environment to human body.

Values for the convective heat transfer coefficient h_w have been derived analytically, measured on a heated copper manikin placed in water or determined from experimental data on human. RAPP [6] presented values for h_w of 105 $Wm^{-2}C^{-1}$ in still water, increasing nearly linearly to 411 $Wm^{-2}C^{-1}$ at 0.5 ms^{-1}.

CHAPTER 3
NUMERICAL SIMULATION

The mathematical model for human thermoregulation involves both a passive system and a controlling system. Commonly, the geometrical and anatomical representations of the body and mathematical expressions of the heat transfer within the body and between the body and its environment are referred to as the passive system. The mathematical representation of the regulatory mechanisms by which the body regulates its heat exchanges to control the body temperature is referred to as the controlling system. The model is expressed in a form of computer simulation, which is written in FORTRAN programming language.

For the present study, a 29-node model is used. The development of this model is derived from the Stolwijk and Hardy model [1], particularly in aspects of body heat flow analysis and mechanisms for thermal regulation. However, Stolwijk and Hardy model is only modeling of temperature control of human in air environment, whereas, the developed model has included the air environment as well as water environment. In addition, the six-element body representation by Stolwijk and Hardy is replaced by seven-element representation, which the "trunk" part has been divided into "thorax" and "abdomen". The purpose is to allow simulation for half body water immersion.

3.1 CONTROL SYSTEM

Figure 3.1 shows the anatomical representation of the human body. As shown in the figure, the body is divided into seven segments (I), i.e. head, thorax, abdomen, arm (included arm and forearm), hand, leg (included thigh and calves) and feet. Each of the body segments is further divided into four compartments (N): core, muscle, fat and skin. An additional central blood compartment, representing large arteries and veins, exchange heat with all the other compartment through the convective heat transfer occurring with the blood flow to each compartment. To simplify the model, each compartment is assumed to have direct blood convective heat transfer with the central blood compartment rather than the adjacent body compartments. The total compartments are 29 compartments. For each of the 29 compartments complete heat balance equation must be developed to account for heat flow into and out of the compartments, through conduction, convection, and the metabolism heat production within the compartment. For those compartments in contact with outside environment, equations will be derived to express the heat exchange by evaporation, radiation, and convection. Chapter 2, Mathematical Modeling, has details discussion about general Heat Balance Equation of human being.

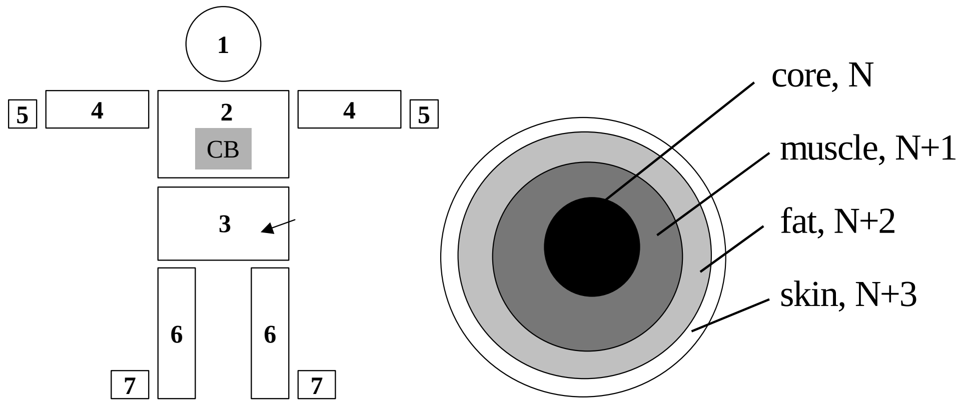

Figure 3.1 Seven-segment human thermoregulation model

The dimensions and thermal properties of each compartment are derived from *Handbook of Physiology ~ Reaction to Environmental Agents* [1]. The average The “Standard man” in the calculation is taken as 172 cm in height and 74.4 kg in weight. Table 3.1 shows the definition of symbols and their dimension used in FORTRAN programming. In numerical calculation, each segment is presented as I and each compartment is presented as N. Therefore, the symbol I in Table 3.1 are refer to the segment, I=1 being the head,I=2, the thorax, I=3, the abdomen, I=4, the arms, I=5, the hands, I=6, the legs and I=7, the feet. The character N is refer to the individual compartment, i.e. N=4*I-3 always indicates the core layer of segment I, N=4*I-2 the muscle layer, N=4*I-1 the fat layer and N=4*I the skin compartment. The central blood compartment is represented by N=29. Table 1 (Appendix A) gives the surface area and weight of each segment together with parameters of weight and heat capacitance for each compartment. The values of heat capacitance are based on a specific heat for the skeleton of 0.58 W.h/kg.°C, 0.70 W.h/kg.°C for fat and 1.05 W.h/kg.°C for all other tissues. The central blood compartment representing the blood in the heart and the great vessels is assumed to contain 2.5 liters of blood at a specific heat of 1.04 W.h/°C. Table 2 (Appendix A) shows the thermal conductance between compartments, basal metabolic heat production and basal blood flow for each compartment (Data are taken from *Handbook of Physiology ~ Reaction to Environmental Agents* [1]).

Table 3.1 Definition of Symbols used in Controlled System.

SYMBOL	**TOTAL VALUE**	**DEFINITION**	**DEMEN-SION (SI units)**
QC(N)	29	Heat capacitance of compartment N	W.h°C^{-1}
QF(N)	29	Rate of heat flow into or from N	W
T (N)	29	Temperature of C	°C
F(N)	29	Rate of change of temperature in N	°C.h^{-1}
MB(N)	28	Basal metabolic heat production in N	W
M(N)	28	Total metabolic heat production in N	W
EV(N)	28	Total evaporative heat loss from N	W
TK(N)	28	Thermal conductance between N and N+1	W. °C^{-1}
TD(N)	28	Conductive heat transfer rate, N to N+1	W
BFB(N)	28	Basal effective blood flow to N	l.h^{-1}
BF(N)	28	Total effective blood flow to N	l.h^{-1}

BCV(N)	28	Convective heat transfer between central blood and N	W
S(I)	7	Surface area of Segment I	m^2
HRD(I)	7	Radiation heat transfer coefficient for Segment I	$Wm^{-2}°C^{-1}$
HCV(I)	7	Air environmental convective heat transfer coefficient for Segment I	$W.m^{-2}°C^{-1}$
H(I)	7	Total environmental heat transfer coefficient for Segment I	$W.°C^{-1}$
HW		Water environmental convective heat transfer coefficient for Segment I	$W.m^{-2}°C^{-1}$
EMAX (I)	7	Calculated maximum rate of evaporative heat loss from Segment I	W
PSKIN (I)	7	Saturated water vapor pressure at skin temperature	Torr
PV	10	Vapor pressure from 5-50°C (from Steam Table)	Torr
WORK		Total metabolic rate required by exercise	W
TAIR		Air temperature	°C
TW		Water temperature	°C
V		Air Movement	$m.s^{-1}$
RH		Relative humidity in air	NONE
PAIR		Water Pressure in air	Torr
TIME		Elapsed time	hr
ITIME		Elapsed time	min
DT		Integration Step	hr
INT		Intervals between outputs	min

3.11 Metabolic Heat Production

Metabolic rate of the brain is estimated about 17% of the basal metabolic rate, and the trunk core accounts for about 60% of the resting metabolic rate. The total skin and musculature to produce 18% of the basal metabolic heat which leaves 5% for the skeleton and connective tissue. Since the resting metabolic rate is taken as 86.5 W for the whole standard man (45.8 $W.m^{-2}$), the head core has a metabolic rate of 14.9 W, the trunk core of 52.6 W and 15.6 W is to be divided between skin and musculature. The full estimated values of basal metabolic rate, MB(N) is shown in Table 2 (Appendix A).

3.12 Convective Heat Exchange Resulting from Blood Flow.

Convective heat transfer occurred between its parts as a result of blood flow. Some regions are characterized as relatively constant blood flow. For example, the brain receives a constant blood flow of about 45 $l.hr^{-1}$. Resting muscle is estimated to require 1.2 $l.hr^{-1}$ of blood flow for each 1.16 W of metabolic heat production, purely on the basis of supplying the needed oxygen. The distribution blood flood to different compartment in different segment including that of different skin areas is shown in Table 2 (Appendix A).

3.13 Heat Exchange with Environment

In air environment, the environmental heat transfer coefficient of each segment is shown in Table 3 (Appendix A). Air velocity considered in terms of the convective coefficient and estimated in Table 3 are for the natural convection. Substitution of proper environmental factors into the heat loss equations enables the model to respond so as to simulate thermoregulatory activity. For the condition estimated in Table 3, the sensible heat loss from the skin of segment I in air environment can be written as

$$(HRD(I)+HCV(I))*(T(4*I)-TAIR) = HA(I)*(T(4*I)-TAIR) \quad (3.1)$$

In water environment, expression HA(I)*(T(4*I)-TAIR) will then be present in HW(I)*(T(4*I)-TW).

3.2 CONTROLLING SYSTEM

A controlling system of the model is developed to simulate human physiological response by body thermoregulation. A closed control loop with set and feedback temperature for each compartment is developed to simulate the four kinds of thermal sensations: vasoconstriction and shivering against cold; vasodilatation and shivering against heat. The actual instantaneous temperature in all the compartments are compared with the set point temperature so that "SIGNAL" can be obtained and then the outputs of "WARM" or "COLD" can be determined as the following:

SIGNAL(N) = T (N) – TSET(N) + RATE(N)*F(N) (3.2)

In the first approximation, the SIGNAL is thus equal to the difference between the instantaneous temperature T(N) and the reference temperature TSET(N). For appropriate compartment where dynamic sensitivity of the thermoreceptors is quantitatively known, the dynamic term RATE(N)*F(N) can assume positive or negative values. T(N) and F(N) are continuously computed from the passive system, and TSET(N) and RATE(N) are controlling system characteristics supplies as initial constants.

WARM(N) = SIGNAL(N),	if	SIGNAL>0;
WARM(N) = 0,	if	SIGNAL<=0;
COLD(N) = -SIGNAL(N),	if	SIGNAL<0;
COLD(N) = 0 ,	if	SIGNAL>=0;

Table 3.2 Shows the definition of all symbol used in the controlling system.

Table 3.2 Definition of Symbols used in Controlling System.

SYMBOL	TOTAL VALUE	DEFINITION	DEMEN-SION (SI units)
SIGNAL(N)	29	Output from thermoreceptors in compartment N	°C
WARM(N)	29	Output from warm receptors in N	°C
COLD(N)	29	Output from cold receptors in N	°C
TSET(N)	29	Set point of temperature for receptors in N	°C
RATE(N)	29	Dynamic sensitivity of thermoreceptors in N	
WARMS		Integrated output from skin warm receptors	°C
COLDS		Integrated output from skin cold receptors	°C
SWEAT		Total efferent sweat command	W
CHILL		Total efferent shivering command	W
DILAT		Total efferent skin vasodilatation command	$l.hr^{-1}$
STRIC		Total efferent skin vasoconstriction command	NONE
SKINR(I)	7	Fraction of all skin receptors in Segment I	NONE
SKINSW(I)	7	Fraction of sweating command applicable to skin of Segment I	NONE
SKIND(I)	7	Fraction of vasodilatation command applicable to skin of Segment I	NONE
SKINC(I)	7	Fraction of vasoconstriction command applicable to skin of Segment I	NONE
WORKM(I)	7	Fraction of total work done by muscles in Segment I	NONE
CHILLM(I)	7	Fraction of total shivering occurring in muscle of Segment I	NONE
CSW		Sweating from head core	$W.°C^{-1}$
SSW		Sweating from skin	$W.°C^{-1}$
CDIL		Vasodilatation from head core	$l.h^{-1}.°C^{-1}$
SDIL		Vasodilatation from skin	$l.h^{-1}.°C^{-1}$
CCON		Vasoconstriction from head core	$°C^{-1}$
SCON		Vasoconstriction from skin	$°C^{-1}$
CCHIL		Shivering from head core	$W.°C^{-1}$
SCHIL		Shivering from skin	$W.°C^{-1}$
PSW		Sweating from head core and skin	$W.°C^{-2}$
PDIL		Vasodilatation from skin and head core	$l.h^{-1}.°C^{-2}$

PCON		Vasoconstriction from skin and head core	°C^{-2}
PCHIL		Shivering from skin and head core	°C^{-2}

The distribution of receptors is different in individual compartment. This is to ensure every different part of compartment can have different temperatures especially important in skin compartment. Thus, the value for fraction of all skin receptors in particular segment I , SKINR shown in Table 4 (Appendix A) have been estimated from experiment by Nadel et.al [1]. The distribution of vasodilatation and vasoconstriction is also not uniform over the skin area. The relative distribution of sweat secretion, in the absebce of information based on local secretion measurements is estimated by the distribution od sweat glands. Table 4 also shows the value of SKIND, SKINC and SKINSW.

The total warm receptor output from the skin, WARMS, is obtained by summing of SKINR(I)*WARM(4*I) for the skin compartments of all segment. The total cold receptor output can be calculated from the same summation.

$$\text{WARMS}=\sum \text{SKINR(I)*WARM(I)} \qquad \text{where I = 1 to 7}$$

and

$$\text{COLDS}=\sum \text{SKINR(I)*COLD(I)} \qquad \text{where I = 1 to 7}$$

Based on a central temperature signal from head core and the integrated signal from the skin, the efferent outputs of the controlling systems are determined, respectively, for the four thermal reactions:

SWEAT = CSW*SIGNAL(1)+SSW*(WARMS-COLDS)+PSW*WARM(1)*WARMS

DILAT = CDIL*SIGNAL(1)+SDIL*(WARMS-COLDS)+PDIL*WARM(1)*WARMS

CHILL=(CCHIL*SIGNAL(1)+SCHIL*(COLDS-WARMS))*PCHIL*(WARMS- COLDS)

STRIC = CCON*SIGNAL(1)+SCON*(COLDS- WARMS)+PCON*COLD(1)COLDS

The controlling system equations all have a first term consisting of the product of control coefficient and a central temperature signal, a second term consisting of the product of a control efficient and an integrated skin temperature signal, and a third term consisting of the product of control efficient, a central temperature signal, and a skin temperature signal. These expression will become negative under some circumstances, therefore, any negative values of SWEAT, DILAT, CHILL or STRIC will be set to zero in numerical calculation.

3.21 Metabolic Heat Production – Work and Chill

The basal metabolic rates for all core compartments can be expressed in numerical form as the following:

$$M(N) = MB(N) \tag{3.3}$$

These expression shows that the basal metabolic rate for all core compartments is not change under the relatively short-term condition.

For the muscle layer,

$$M(N+1) = MB(N+1)+WORKM(I)*(WORK)+CHILLM(I)*CHILL \tag{3.4}$$

The metabolic heat production in muscle compartment is the sum of the basal heat production MB(N+1), and the heat production rates assigned to muscular work done and shivering thermogenesis. Table 5 (Appendix A) shows the estimated values of WORKM and CHILLM, which is taken from the Handbook of Physiology [1]

In the fat and skin compartments, it is assumed that the basal metabolic heat production does not change in the conditions to be evaluated by the model, so that

$$M(N+2) = MB(N+2) \tag{3.5}$$

$$M(N+3) = MB(N+3) \tag{3.6}$$

3.22 Blood Flow

The convective heat transfer by blood flow plays a very important role in the thermal response to internal and external stresses. The blood flow to the core compartment is assumed to be remain at the basal values:

$$BF(N) = BFB(N) \tag{3.7}$$

This expression ignores the fact that blood flow to the trunk core can be reduced during exercised stress, but the blood flow to these compartments is considerably in excess of that required to supply oxygen to these compartments, and thus only small thermal gradients can exist between core compartments.

Unlike the core compartment, muscle compartment can have widely different metabolic rates and, consequently, variations in blood flow as well. Under conditions in which heat loss in exercise is mostly from evaporation of sweat, the working muscle is about 1.0 °C above that of the arterial blood supplying oxygen. If venous blood leaves at muscle temperature, then every liter of blood contains about 200 ml O_2 which, if completely scavenged, could produce 1.16 W.h of heat. As the result, the following equation expresses the blood flow to the muscle compartment.

$$BF(N+1) = BFB(N+1) + M(N+1) – MB(N+1) \tag{3.8}$$

Blood flow to the fat layer is not very high in basal value, and it is not effectively changed as a result of thermoregulatory adjustments

$$BF(N+2) = BFB(N+2) \tag{3.9}$$

Skin blood flow is highly dependent on the thermoregulatory controller. The basal blood flow at thermal neutrality can be reduced to very low values through vasoconstriction, and increased through vasodilatation. The expression for local skin blood flow then becomes

$$BF(N+3) = ((BFB(N+3) + SKINV(I)*DILAT)/(1. + SKINC(I)*STRIC)) *2.** (SIGNAL(N+3)/10.) \tag{3.10}$$

In this expression, the weighted DILAT central drive is added to the basal blood flow. The weighted constrictive tone operates through a resistance and thus is entered as a divisor. The local skin temperature effect (2**(SIGNAL(N+3/10)) then acts on the total flow drive multiplying it by unity in neutral condition (SIGNAL(N+3)=0), by less than unity at skin temperatures below normal and by more than one at skin temperature above the neutral value.

3.23 Evaporative Heat Loss and Sweating

For the resting subject in air environment, evaporative heat loss occurred through skin diffusion and respiratory system. Respiratory water loss is a function of water pressure in the inspired air (PAIR) and the ventilation volume. The ventilation volume is closely related to the metabolic rate. Thus, the evaporative heat loss from respiratory water loss can be as

$$EV(5) = (86.4+WORK)*(0.0026749)*44.0-PAIR) \qquad (3.11)$$

Where 44.0 is the vapor pressure in expired air.

There is no evaporation heat loss occurred in other core, muscle and fat compartment, thus

$$EV(N) = EV(N) = 0 \qquad \text{(besides EV(5))} \qquad (3.12)$$

$$EV(N+1) = EV(N+1) = 0 \qquad (3.13)$$

$$EV(N+2) = EV(N+2) = 0 \qquad (3.14)$$

From eq.2.2 (Chapter 2), the evaporative heat loss through skin diffusion (ED) for segment I can be rewritten in numerical form as the following:

$$ED(I)=(1.6944\times10^{-4})*HFGSKIN*SA(I)*(PSKIN-PAIR) \qquad (3.15)$$

Where HFGSKIN is calculated by interpolation from the steam table.

The different skin compartments receive a sweating drive, SWEAT from the central controller. The local response in a skin compartment depends on the surface area and on the number of sweat glands present, expressed by SKINS(I). The evaporative heat loss through sweating (ES) then can be expressed as

$$ES(N+3) = SKINS(I)*SWEAT)*2.**((T(N+3)-TSET(N+3)) \qquad (3.16)$$

The maximum evaporative heat loss (EMAX) from a totally wet skin is proportion gradient from the water vapor on the skin surface to the water vapor in the ambient air and can be described by the relation

$$EMAX = \lambda .h_D(PSKIN\text{-}PAIR) \quad (W.m^{2)} \qquad (3.17)$$

where λ is latent heat of sweat in 0.68 $W.h.g^{-1}$: h_D is mass transfer coefficient (for diffusion of water vapor) in $m.hr^{-1}$.

The wetted area of the skin (A_w) us defined as the area of skin, if covered with sweat, would provide the observed rate of skin evaporation under the prevailing condition. Thus by definition

$$EV = A_w.EMAX/A_{total} \qquad (3.18)$$

Skin wettedness (w) is defined as the ratio of A_w/A_D. Thus

$$w = A_w/A_D = EV/EMAX \qquad (3.19)$$

Skin wettedness ranges from a certain minimum value, which occurs when there is no evaporative heat loss by regulatory sweat (i.e., ES=0), to a maximum theoretical value of unity. A theoretical minimum value of zero would occur if the skin were completely impermeable to water vapor. At the minimum w value the evaporative heat loss from the skin surface is entirely due to the diffusion of water vapor (ED), evaporated within outer layers of the skin. The ED is also directly proportional to the value of EMAX. When regulatory sweating begins, evaporative heat loss may occur both by diffusion (ED) as well as by the evaporation of sweat (ES). When the skin is completely wet (i.e., w =1), ED no longer occurs and EV is attributed entirely to regulatory sweating (ES). The ratio ES/EMAX describes the skin wettedness (w_S) due to sweating, i.e.,

$$w_S = ES/EMAX \qquad (3.20)$$

and the ratio ED/EMAX is the skin wetttedness due to diffusion (w_D), i.e.,

$$w_D = ED/EMAX \quad (3.21)$$

The total wettedness (w) any time is given by

$$w = w_D + (1 - w_D)\, w_S \quad (3.22)$$

By substitute Eq. (3.20) and Eq. (3.21) into Eq. (3.22), we get

$$EV=ES+ED-(ES*ED/EMAX) \quad (3.23)$$

CHAPTER 4

EXPERIMENTS

4.1 INTRODUCTION

Numerous studies have simulated the human physiological response in water immersion. In order to validation of the simulation result, experiments have been conducted on human subjects to measure the oral and skin temperature. Oral temperature can be used to compare with core temperature that was calculated in the simulation whereas skin temperature will be directly validated by simulation results.

4.2 METHOD

4.21 Instrumentation

Figure 4.1 illustrates the experimental instrumentation. Oral temperature (T_{oral}) was measured using a Copper-Constantan thermocouple directly inserted into mouth. Skin temperature was also measured by same thermocouple placed on the following sites: face, chest, abdomen, arm, forehand and leg (thigh). The measured sites were insulated with a small patch of plastic and masking tape. A layer of water strong bandages were also pasted over the patch to prevent them getting out from water. The area weighted mean skin temperature, T_{sk} was calculated by assigning the following regional percentages: face 7%, chest 17.5%, abdomen 17.5%, arm 14%, hand 5% and thigh 39%. Signal were amplified, noise filtered and then collected and digitized (by NEC digital recorder, model DR-F2A) at 1-s intervals and recorded in a floppy disk. The data in Volt will then converted to temperature in Celsius by computer programming (*see* Programming 2: Conversion Volt to Celsius, Appendix B).

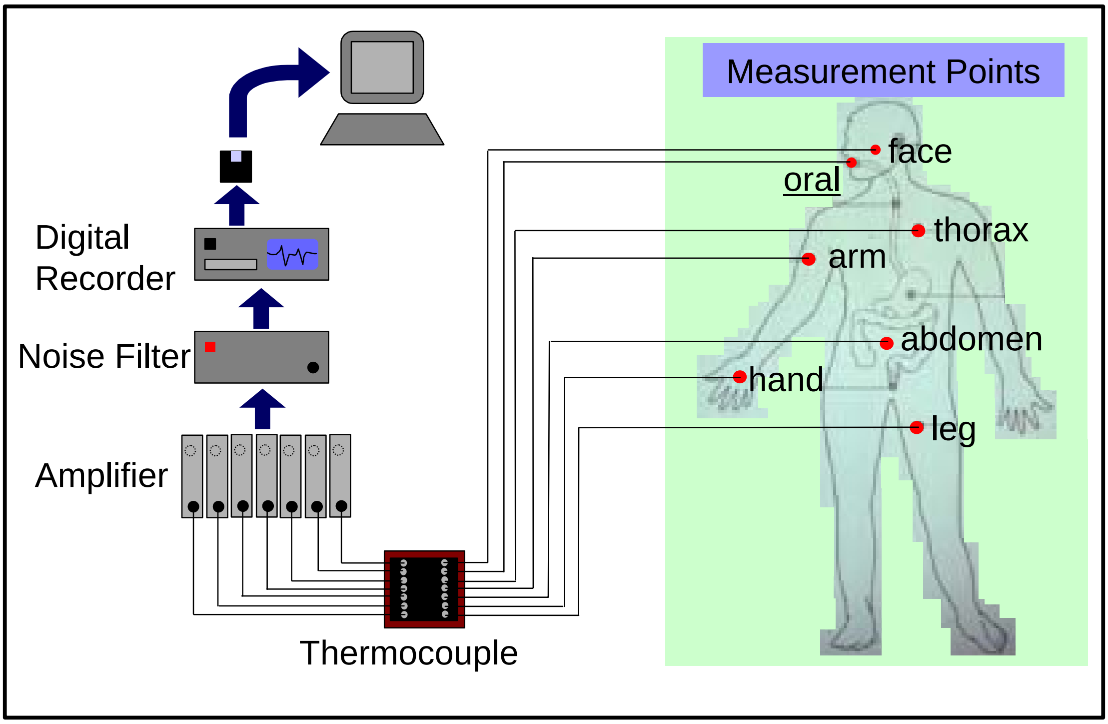

Figure 4.1 Experiment apparatus

4.22 Experiment procedure

The experiments were done in a single apartment where the room and bath room temperature was around 23 to 25 °C and relative humidity was 50 to 60%. Subjects were taking bath in a one person use bathtub. Subjects were nude (wearing only swimming trunk is assumed to be nude) and were instrumented appropriately before the experiments were started. When the experiment was started, subject was resting by sitting on a chair in the room for 10 minutes (pre-immersion phase). The subject then immersed into water in the bathtub with set water temperature for 15 minutes (water immersion phase). After the water immersion, subjects then sat in the room for 30 minutes that allow the body and skin temperature recovered back to the normal condition (recovery phase).

4.23 Experiment Cases

There were 3 variable parameters in the experiments i.e. subjects, water temperature and body part of immersion. However, only one of the three parameters was become variable parameter and the other two were constant. Therefore, there were 3 cases in the experiments where in the first case, subjects were variable whereas water temperature and body part of immersion were set to constant. In the second case, water temperature was variable and subjects and body part of immersion were set to constant. Finally, in the last case, body part of immersion was variable whereas subjects and water temperature were set to constant.

Case 1:

Variable: Subjects

Constant: Water temperature and body part of immersion.

Four experiments with different subjects were carried on in this case. Four male subjects A, B, C and D, in theirs 20s with details individual particular showing in Table 4.1 participated in the experiment.

Table 4.1: Subjects Particular and Environmental Conditions

SUBJECT	PERSONAL DETAILS			ENVIRONMENTAL COND. (Temp. & RH)		
	Height(cm)	Weight(kg)	Ethinic	Room (before)	Bath Room	Room (recovery)
A	172	68.5	Asian	24.6 C, 49%	23.5 C, 50%	24.7 C, 48%
B	173	69	Caucasian	25.2 C, 64%	25.4 C, 64%	25.7 C, 66%
C	168	64	Asian	25.2 C, 61%	25.4 C, 66%	24.7 C, 66%
D	174	70	Asian	23.2 C, 55%	23.6 C, 60%	23.7 C, 61%
STANDARD*	172	74.4	-	24.6 C, 57%	24.5 C, 60%	24.7 C, 60%

Water temperature was fixed to 40°C and the immersions were done by whole body immersion with only head out for the entire four experiments. Table 4.1 shows also the environmental conditions (temperature and relative humidity) while the experiments were carried on.

Case2:

Variable: Water temperature

Constant: Subjects and body part of immersion.

Only subject A was participated in these experiments and immersion was whole body immersion with head out. Subject A was immersed in water at 28, 40 and 44 °C in different day. Water temperature at 40°C is the normal hot bath water temperature recommended by non-technical researcher. Cold water (relatively to skin temperature) at 28°C was selected to validate the experiment and simulation results for the cold water. For the same reason, water temperature at 44°C was selected for the extremely hot water condition.

Case 3:

Variable: body part of immersion

Constant: Subjects and water temperature

In this case, subject and water temperature were fixed to subject A and 40°C. There were two experiments were carried out, first one was whole body immersion with head out and the other was half body immersion (until chest level). This experiment is to investigate the different between the different part body of immersion where some non-technical researcher suggested that half body immersion hot bath is beneficial to human.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 EXPERIMENTAL RESULTS

Case 1

The experimental results of mean skin temperature of four subjects, A, B, C and D were shown in Figure 5.1. It can be seen that mean skin temperature. T_{sk} remained stable and constant (around 32 to 34 °C) during the 10 minutes period prior to water immersion,. Immediately upon immersion T_{sk} increased sharply to about 38 °C in 5 minutes time and kept on increasing slowly until the end of immersion. Immediately the subjects left the water, T_{sk} fell sharply to normal mean skin temperature of around 32°C in 5 minutes time and kept on decreasing slowly until it reached a constant state at the end of recovery phase.

No significant different of T_{sk} were observed among the four subjects. The minor different of T_{sk} in the pre-immersion and recovery phase was due to the different individual particular (such as weight, height, fat percentage etc) and the slightly different environmental conditions (Table 4.1) when the experiment was carried out.

The experimental results of oral temperature for the four subjects are indicated in Figure 5.2. As shown in the figure, the oral temperatures, T_{oral} have reached a constant state of around 35°C to 36°C before the immersion. The head-out immersion only induced small increase (about 1 to 1.5°C) in oral temperature. After the immersion, the oral temperature slightly increased in the first 1 to 2 minutes and then decreased slowly and returned to pre-immersion values within 20 minutes of leaving the water.

Subject B, C and D show very consistent results whereas there was not so good result was taken from subjects A. The inconstant of experimental data is due to the difficulty of oral temperature measurement by using thermocouple. This is because the saliva inside the mouth affected the accuracy of temperature measurement.

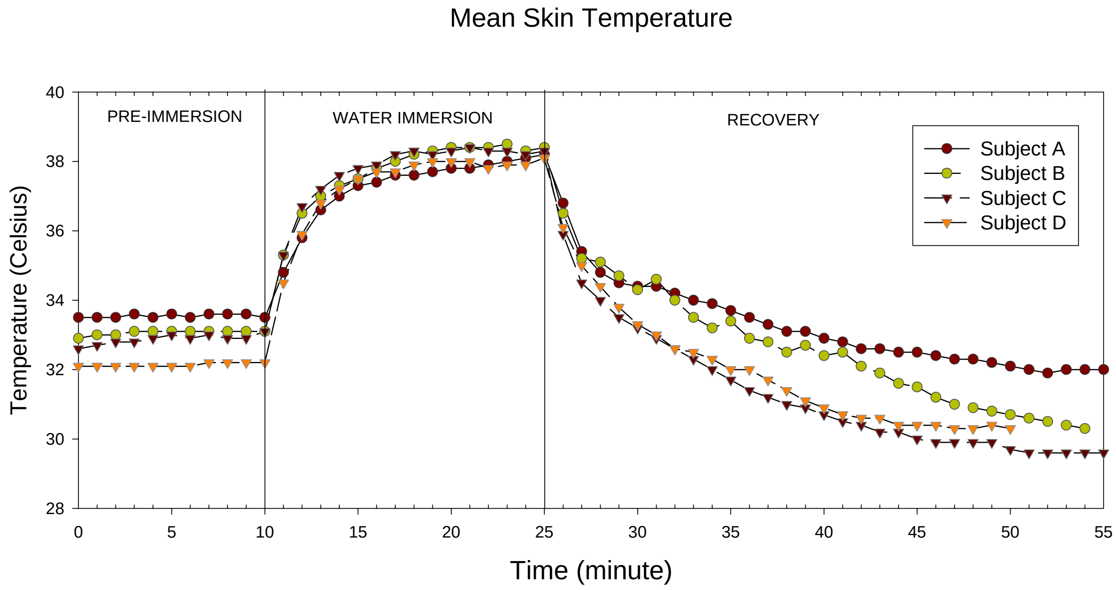

Figure 5.1 Experiment Results: Mean Skin Temperature of Different Subjects

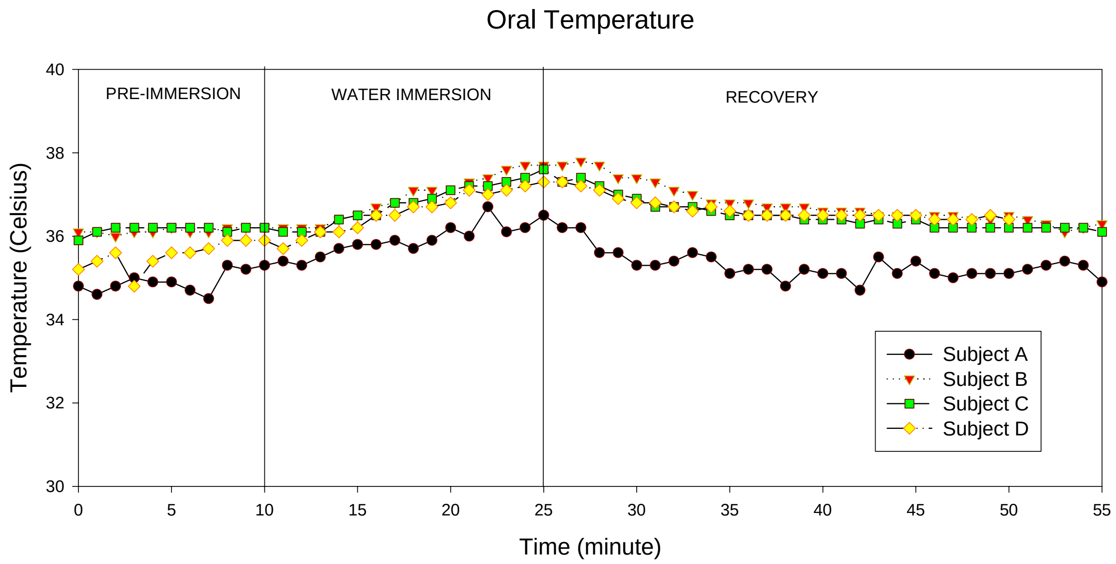

Figure 5.2 Experiment Results: Oral Temperature of Different Subjects

Case 2

Figure 5.3 shows the experimental results of mean skin temperature for different water temperature conditions (44, 40 and 28°C). For water temperature of 44 and 40 °C, T_{sk} increased sharply immediately upon immersion whereas T_{sk} decreased for water temperature of 28 °C. In the recovery phase, for higher water temperature of 44 and 40 °C, T_{sk} fell sharply to normal mean skin temperature of around 35°C in 5 minutes time and kept on decreasing slowly until it reached a constant state at the end of recovery phase. On the other hand, for lower water temperature of 28 °C, T_{sk} kept on decreasing and only reached stable T_{sk} at the end of recovery phase.

The oral temperature profiles are given in Figure 5.4. It is obvious that T_{oral} increased tremendously from 35.0 °C upon immersion to 39.6 °C at the end of immersion. For water temperature of 40 °C, even though the data is inconstant (increasing and decreasing) from time to time, it can be seen clearly that T_{oral} increased in water immersion phase and decreased after the immersion. The experimental results of T_{oral} for water temperature of 28 °C were rather inconstant, but in generally it fluctuated at the line of oral temperature of 35°C. This indicates that there was no significant change of oral temperature profile for the immersion of 28°C water temperature condition. The inconstant of experimental data is due to the same reason as indicated in *5.1 Experiment – Case 1*. This also suggests that thermocouple is not a good device to measure oral temperature.

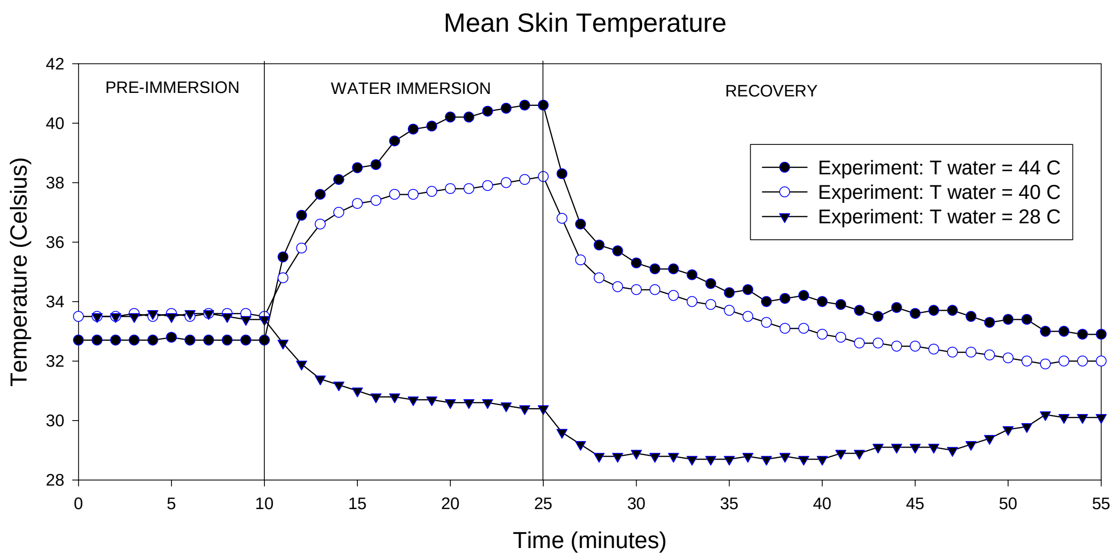

Figure 5.3 Experiment Results: Mean Skin Temperature of Different Water Temperature Conditions

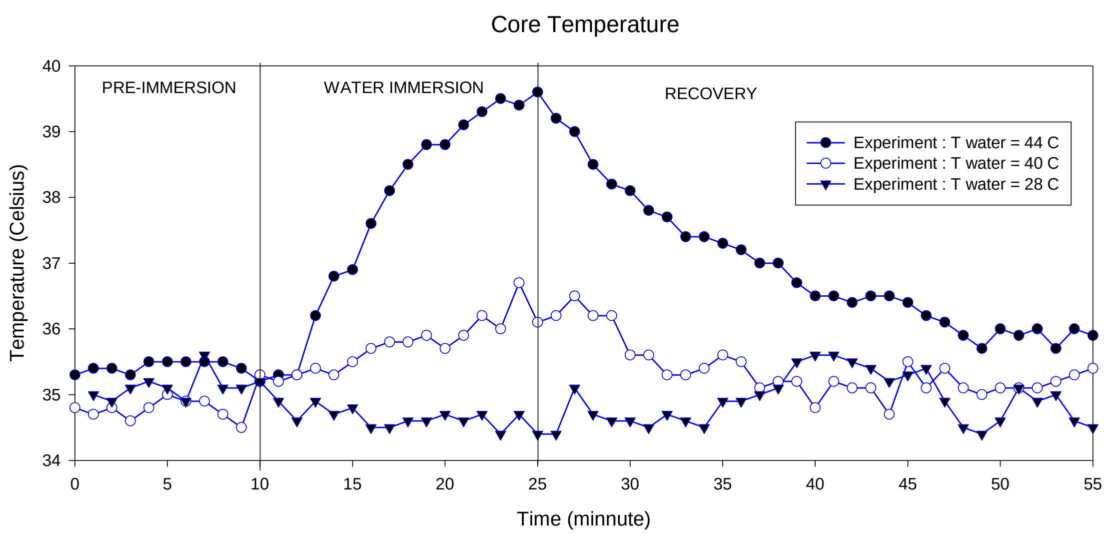

Figure 5.4 Experiment Results: Oral Temperature of Different Water Temperature Conditions

Case 3

Some non-academic researcher suggested that taking half body (until chest level) immersion bath can be more relaxing than whole body immersion. In order to see the physiological response of human in half body immersion, experiments were carried out. Figure 5.5 are results for mean skin temperature T_{sk} with different part body of immersion i.e. either whole body immersion with head out or half body immersion. It can be seen that in both cases, T_{sk} has same profile. However, in the water immersion phase, T_{sk} for head-out whole body immersion is much higher than half body immersion, which is about 2 °C higher at the end of immersion. In recovery phase, T_{sk} for half body immersion recovered to that of pre-immersion phase much faster than head-out whole body immersion.

The experimental oral profile for the both body part of immersion are given in figure 5.6. Similarly, the less efficient performance of the measurement by thermocouple caused the experimental data rather inconstant. However, it still can be seen that T_{oral} fluctuated around the temperature line of 36°C for half body immersion whereas in head-out whole body immersion, T_{oral} increase slowly upon immersion and decreased to that temperature of pre-immersion phase after immersion.

The half body immersion that has much less increasing in T_{sk} and no increasing in T_{oral} and faster recovery suggest that half body immersion can be more relaxing bath and can cater for higher water temperature.

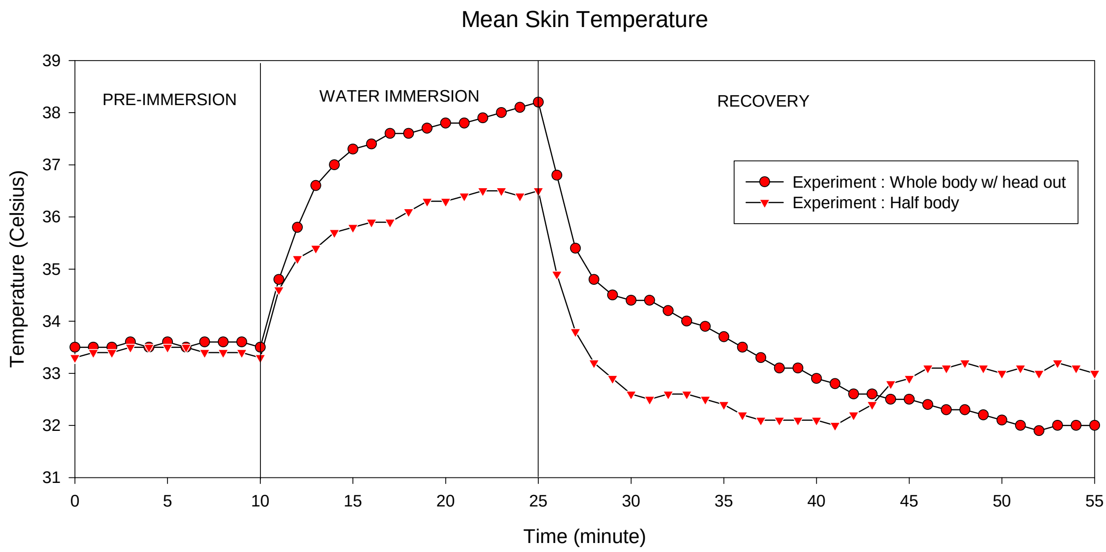

Figure 5.5 Experiment Results: Mean Skin Temperature of Different Part of Body Immersion

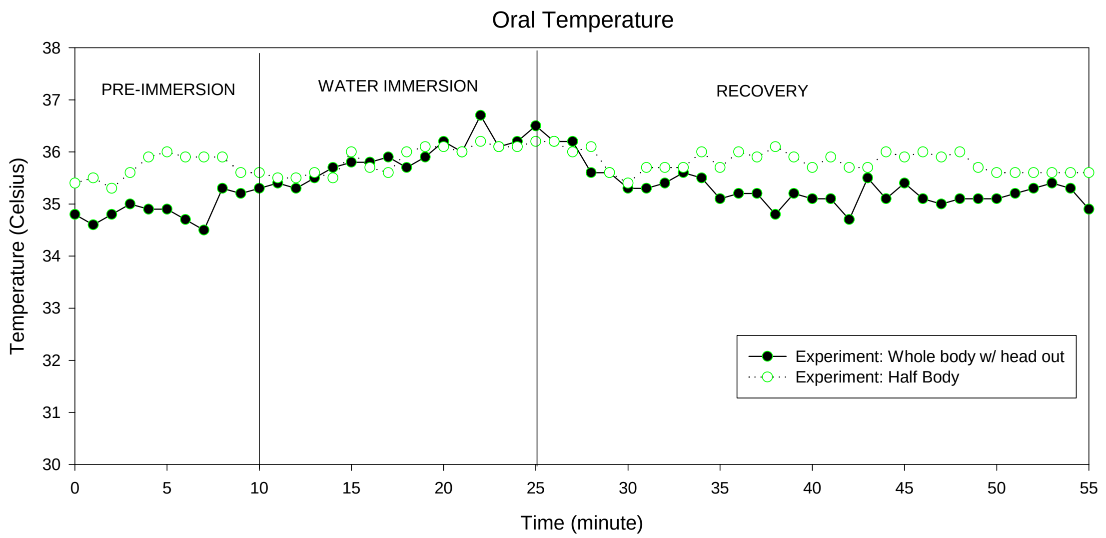

Figure 5.6 Experiment Results: Oral Temperature of Different Part of Body Immersion

5.2 EXPERIMENTS VS SIMULATIONS

The simulation results are validated with experiment data.

Case 1

The human` temperature simulation in pre-immersion phase is begun with mean skin temperature $T_{sk}$ of 34°C and core temperature, $T_{core}$ of 37°C. In order to let the simulated human` temperature get equilibrium with the experiment environment condition, the human is simulated for 60 minute period before the immersion. Figure 5.7 shows the last 10 minute simulation result of T_{sk} in pre-immersion phase and the comparison between simulation and experiments results. It can be seen that the predicted T_{sk} matches well with the experimental results especially in water immersion phase. This suggests that the predicted mean skin temperatures are practically accurate and useful. However, it is noticed that the predicted T_{sk} is slightly higher than experiment results for all subjects in recovery phase. The deviation is due to small measurement error in experiment. The bandages that were pasted on top the skin got wet when the subjects immersed into water. The wet bandage would not dry immediately after the immersion in the recovery phase. As the result, the wet bandage cooled down the skin surface that consequently decreased the skin temperature. Thus, the measured skin temperatures were lower then the actual skin temperature.

The "cooling effect" of bandage is given in Figure 5.7, where comparison between experiments with dry bandage (change wet bandage to dry one immediately after immersion), and the one with wet bandage. It can be seen that by changing the bandage to dry one, the mean skin temperature recovered very fast to normal mean skin condition. The sudden drop of T_{sk} immediately after the immersion was due to the time that changing the wet bandage to dry bandage.

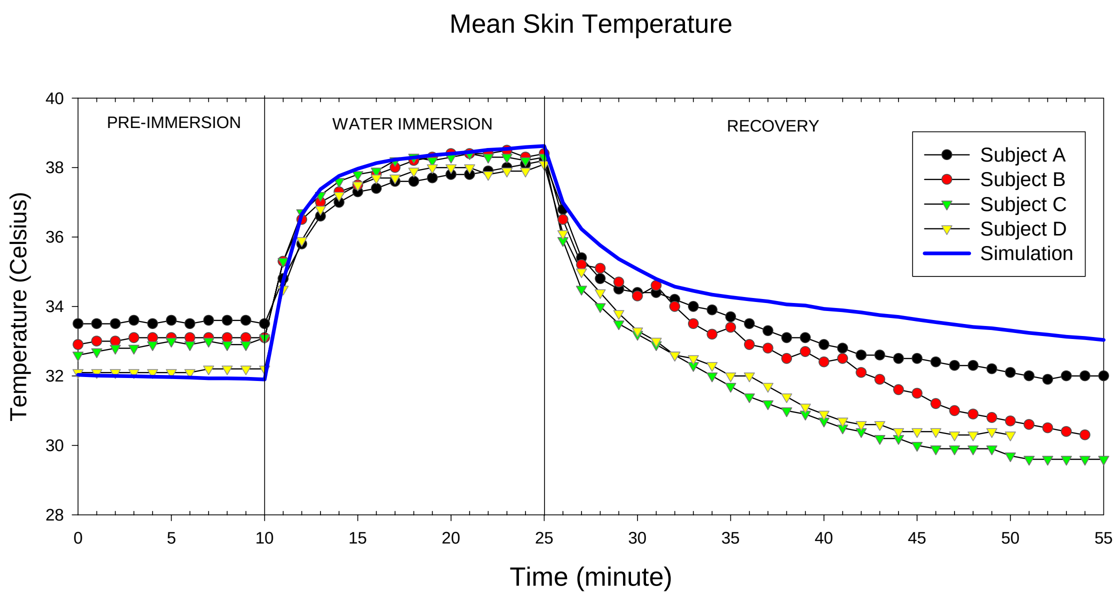

Figure 5.7 Experiments VS Simulation Results: Mean Skin Temperature of Different Subjects

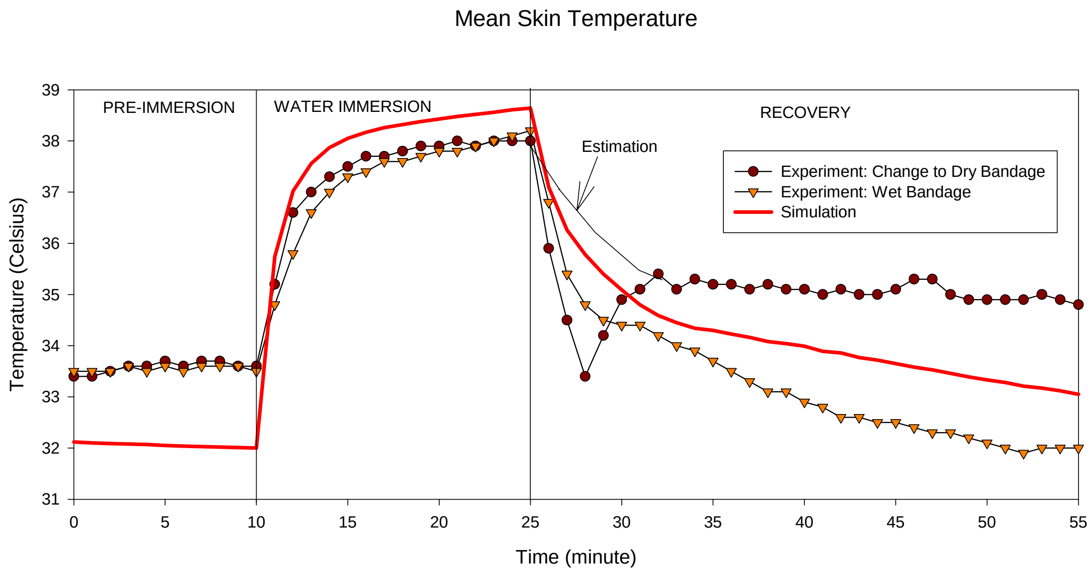

Figure 5.8 Comparison between experiment with dry bandage and wet bandage usage with simulation result.

The comparison of core temperature in simulation and oral temperature in experiment data are given in Figure 5.9. One important point has to stress that oral temperature is not equal to core temperature and in fact core temperature is always higher than oral temperature. Oral temperature is measured during the experiments but not core temperature because no experiment apparatus is available for measurement without consultancy from medical specialist. It can be seen from the diagram that the predicted core temperature always higher than oral temperature and follow the same trend of increasing and decreasing. This suggest that the predicted core temperature is reasonable accurate.

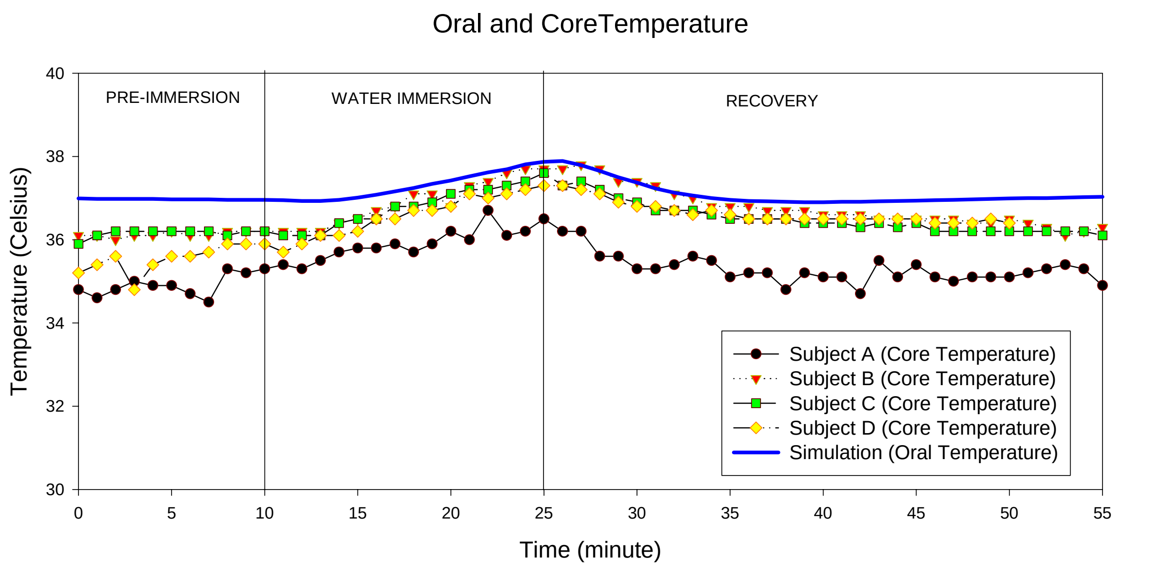

Figure 5.9 Experiments VS Simulation Results: Oral and Core Temperature of Different Subjects

Case 2

In order to test the performance of the model in predicting the results of mean skin temperature, T_{sk} and core temperature T_{core}, in different water temperature conditions, a comparisons was made between simulation and experimental data which is given in Figure 5.10. It can be seen that the simulation results follows exactly the trend of experimental results, i.e. T_{sk} increased when water temperature increased and T_{sk} decreased when water temperature decreased. In addition, only T_{sk} for the water temperature of 28°C decreased upon immersion, which is also matched with the experimental result very well. However, it is noticed that the predict T_{sk} is slightly higher than experimental data in higher water temperature (44 and 40 °C) and slightly lower than experimental data in lower water temperature (28 °C). The deviation is due to the fact that Subject A has different individual characteristic (such height weight, body fat and etc) with standard man that used in numerical calculation. In recovery phase, experimental data of T_{sk} was always lower than the predicted one and took longer time to recover. The deviation is mainly due to the cooling effect of bandage, which has been discussed in *5.2 Experiments vs. Simulations – Case 1*.

The comparison between simulation and experimental results of oral temperature, T_{oral} are given in Figure 5.11. Similar observations to that from Figure 5.10 can be obtained, i.e. T_{oral} profile of simulation result increased when water temperature increased and decreased when water temperature decreased. However, the performance of experimental results is not so good and this give rise to difficulty of comparison with simulation results.

The good agreement of simulation and experimental result especially for mean skin temperature suggests that the model can be applicable to simulate mean skin temperature and core temperature for different water temperature conditions including cold water.

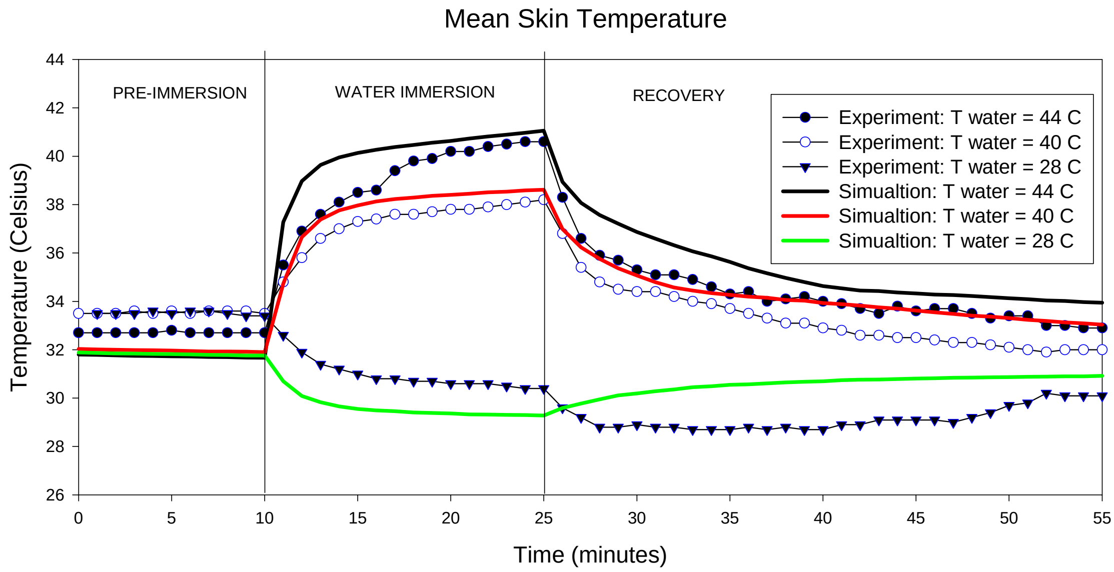

Figure 5.10 Experiments vs. Simulation Results: Mean Skin Temperature of Different Water Conditions

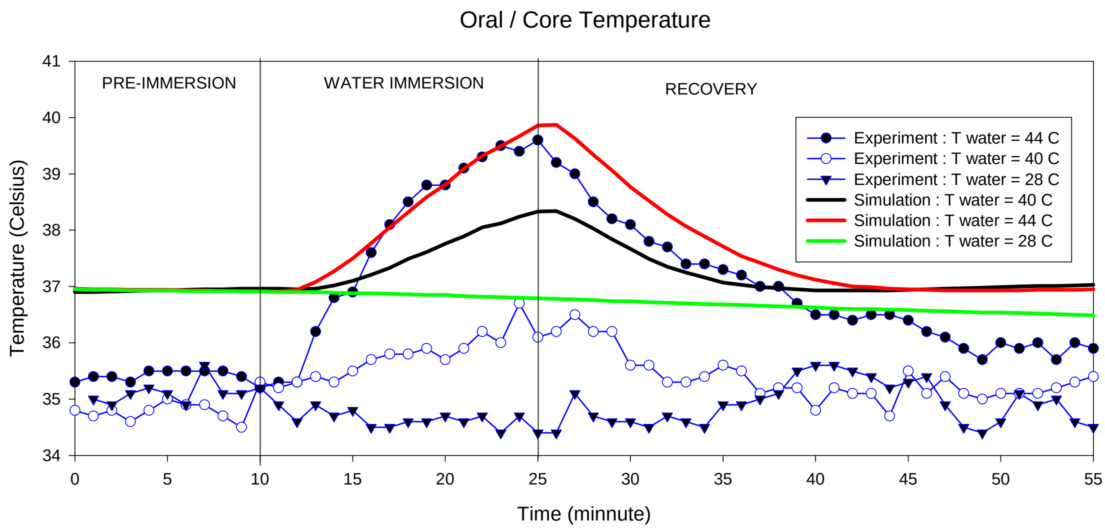

Figure 5.11 Experiments vs. Simulation Results: Oral and Core Temperature of Different Water Conditions

Case 3

Figure 5.12 represents the comparison of T_{sk} between simulation and experimental results. The agreement is good despite the predicted T_{sk} is a little bit higher than experimental data in immersion phase. This is due to the different individual characteristics (such height weight, body fat and etc) with standard man that used in numerical calculation. In the recovery phase, predicted T_{sk} for head-out whole body immersion is always slightly higher than experimental data. The discrepancy was due to the same reason, i.e. cooling effect of bandage, which has been discussed in *5.2 Experiments vs. Simulations – Case 1*.

The comparison between predicted T_{core} and T_{oral} in experimental data are given in Figure 5.13. As indicated in the diagram, both predicted T_{core} and experimental T_{oral} have same profile, i.e. a small increasing (about 1°C) in water immersion phase for head-out whole body immersion whereas no increment of temperature was found in half body immersion phase.

The constant results in the comparison between simulation and experimental data suggest that the model can also be used to predict half body immersion.

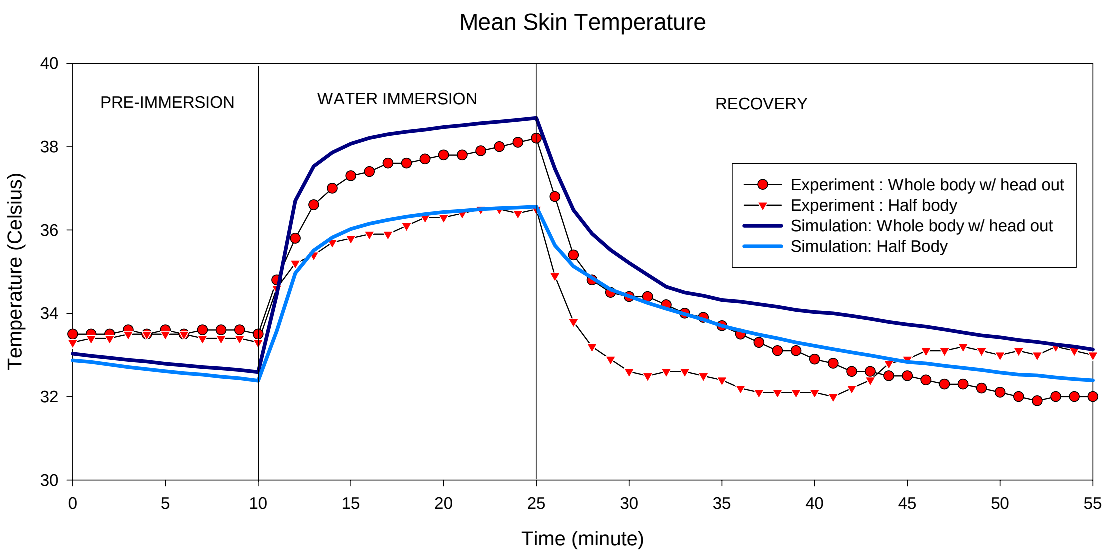

Figure 5.12 Simulation vs. Experimental Results: Mean Skin Temperature of Different Part of Body Immersion

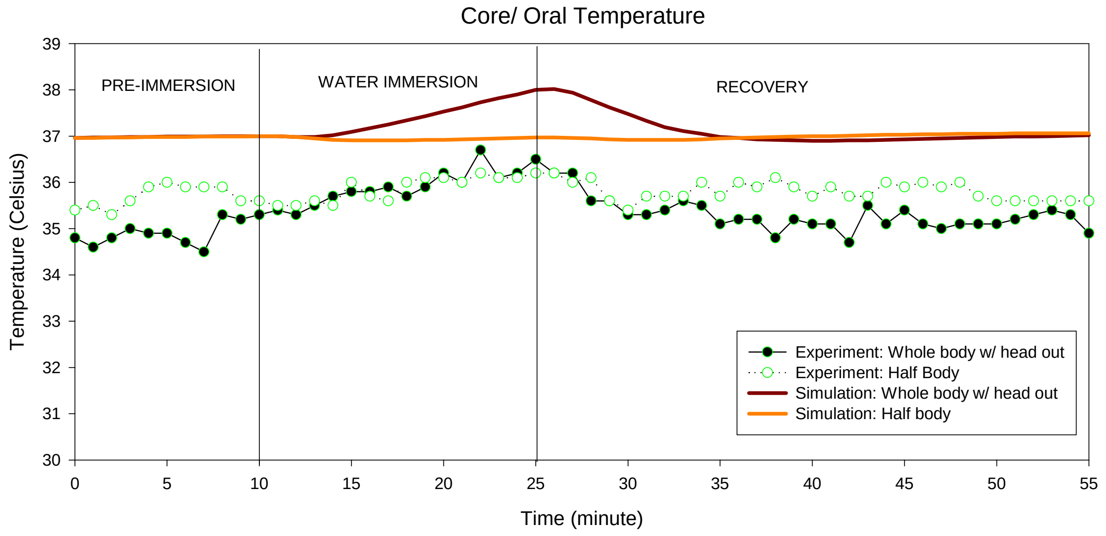

Figure 5.13 Simulation vs. Experimental Results: Oral Temperature of Different Part of Body Immersion

5.3 SIMULATIONS

This model is not only able to predict core and skin temperature but also other human physiology response in water immersion such as metabolism rate, evaporative heat loss and how the heat flow into and out of the body. Examples of the simulation results of these parameters are given in the following diagram. They are the predicted thermal response for whole body immersion with head out in water temperature of 40°C. They are similar environmental and phases conditions with the previous experiments in section *5.1 Experiments*.

Figure 5.14 shows the predicted metabolic rate for the above mentioned conditions. As shown, the metabolism rate is about constant at the around 46 W, which is the resting metabolic rate for normal people. Immediately upon immersion, metabolic rate is raising linearly to maximum at the end of immersion. After the immersion, metabolic rate is decreasing and takes about 15 minutes to reach the resting metabolic rate.

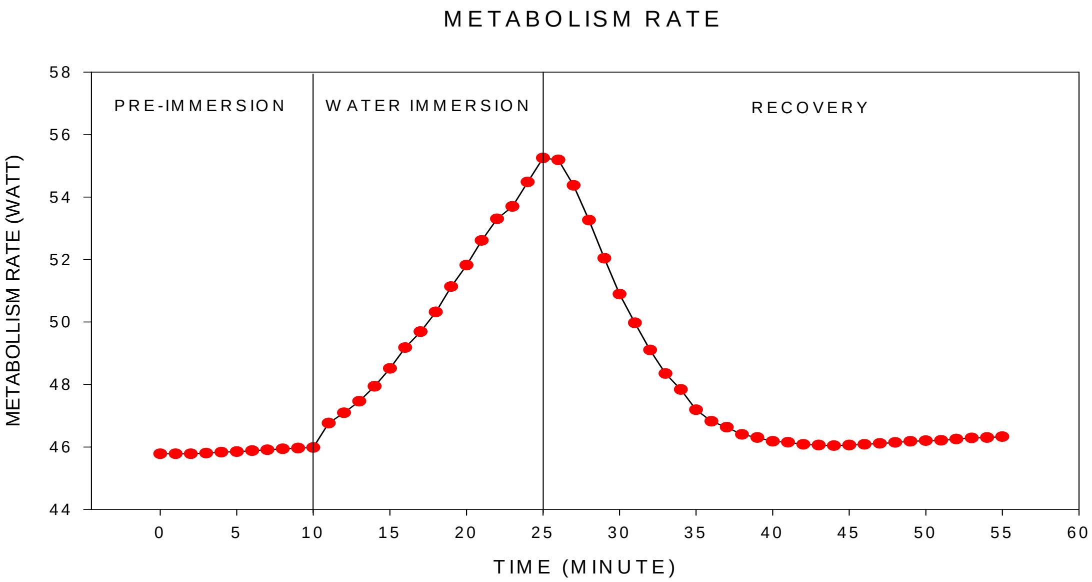

Figure 5.14 Simulation result: Metabolic Rate for Water Immersion at 40°C Temperature.

The simulation results of evaporative heat loss, EV are given in Figure 5.15. It is noticed that at the resting conditions of pre-immersion phase, human is predicted to loss heat to environment mainly through skin diffusion and latent respiration at the rate below 20 W. Upon immersion, EV slightly decrease because evaporative heat loss through skin no longer occurred in water immersion except in small potion of face skin. In this phase, the evaporative heat loss is mainly through latent respiration and it is increasing slowly. This is because the body try to loss heat to environment that against the heat transfer from higher water temperature into body. Once the subject leave water, EV increases sharply to about 170 W mainly from sweating through skin all over the body. It can be then prove that sweating is the important means for human loss heat to environment. EV is decreasing slowly when the subject continuous transfer heat to environment and recover to normal conditions after 15 minutes when core and skin temperature recover to optimum conditions.

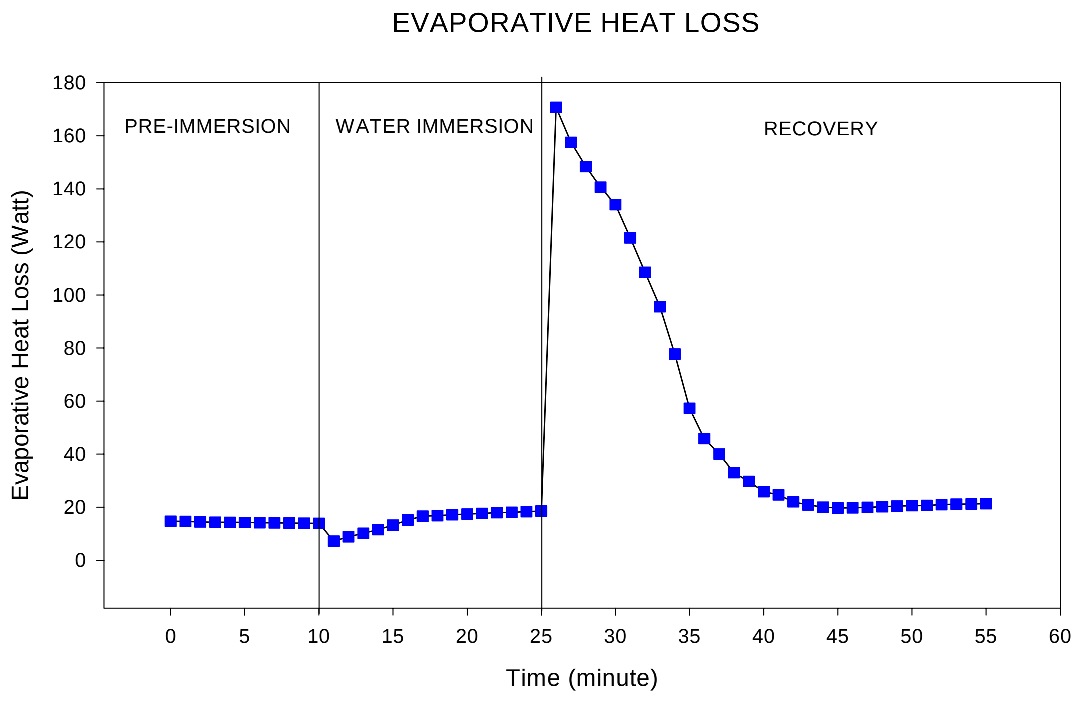

Figure 5.15 Simulation result: evaporative Heat Loss for Water Immersion at 40°C Temperature.

Figure 5.16 represents the simulation results of how heat flow into or out of body in term of body storage of heat. Positive value means that heat is flow from the outside environment into body and on the other hand, negative values represent the heat flow from body to outside environment. It can be noticed that, in the resting conditions in pre-immersion phase, the value of storage of heat is slightly below zero, which indicates that the slightly losing heat to environment in that environment conditions. However, immediately upon immersion, the storage heat of the body has very high value of higher than 400 W, this is due to the sudden heat transfer into the body from the 40 °C warm water. During the immersion phase, it is noticed that even though it has a positive value but it is decreasing. This suggests that, the thermoregulation has activated some mechanism such as vasodilatation and evaporation heat loss through latent respiration to against the increased body and skin temperature. At recovery phase, the subject immediately has a storage of heat of the value of about –200 W. This indicates that the body loss a lot of heat to environment, main through sweating immediately after leaving water. This losses of heat to environment become decreasing as shown in diagram, the value tend to become less negative, and it takes about 15 minute to reach the optimum conditions as it was in pre-water immersion phase.

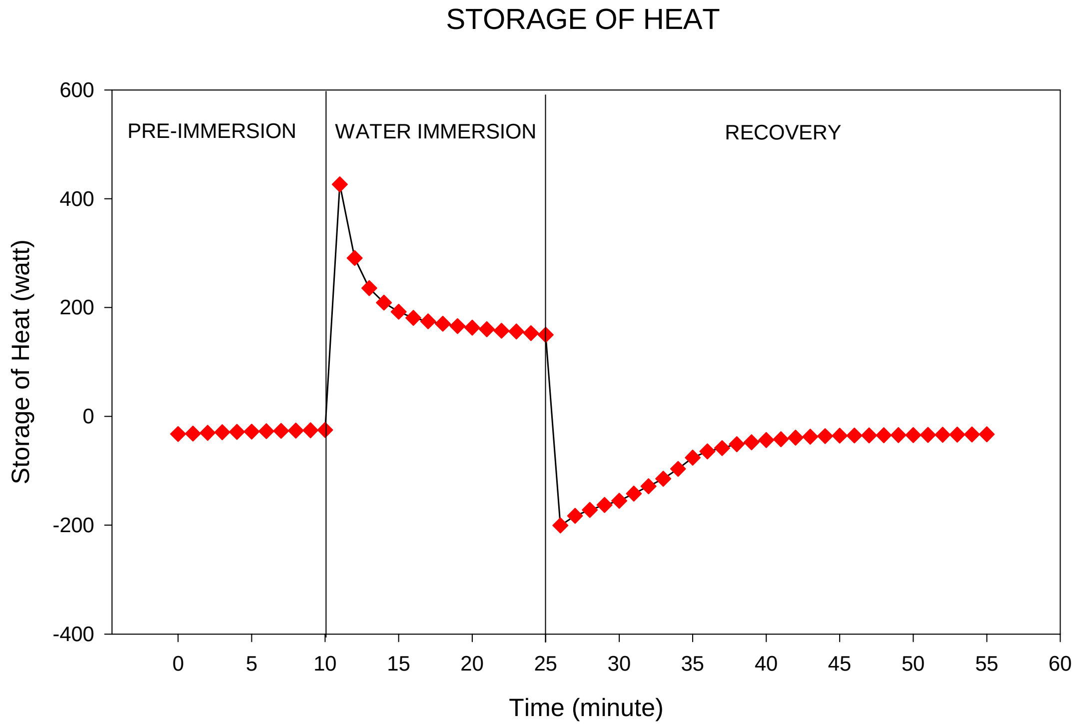

Figure 5.16 Simulation result: Body Heat Storage for Water Immersion at 40°C Temperature.

CHAPTER 6

CONCLUSION

A 29-node human thermoregulation model in water immersion has been developed to simulate the human thermal response such as skin and core temperature, metabolic rate, evaporative heat loss and etc. Meanwhile, the model can predict the mentioned thermal response with different water temperature and part of body immersion. Experimental data of oral and mean skin temperature are used for the validation of the model. The experiments were done in three cases so that validated with simulation result in different criteria. It is noticed that in most cases the simulation results are consistent with experimental data. This concludes that the model can be useful in the simulation of human thermal reaction in water immersion.

APPENDIX

APPENDIX A – TABLES

Table 1: Surface Area, Weight and Heat Capacity of the Four Compartment in each Segment.

Segment	SA	Wt	CORE		MUSCLE		FAT		SKIN	
	m2	kg	Wt,kg	QC,Wh/°C	Wt,kg	QC,Wh/°C	Wt,kg	QC,Wh/°C	Wt,kg	QC,Wh/°C
HEAD	0.1326	4.02	3.01	2.57	0.37	0.39	0.37	0.26	0.27	0.28
THORAX	0.3402	19.25	6.09	5.72	8.95	9.4	3.54	2.47	0.68	0.71
ABDOMEN	0.3402	19.25	6.09	5.72	8.95	9.4	3.53	2.47	0.67	0.70
ARMS	0.2536	7.06	2.25	1.63	3.37	3.54	0.97	0.67	0.48	0.50
HANDS	0.0946	0.67	0.26	0.16	0.07	0.07	0.15	0.10	0.19	0.20
LEGS	0.5966	20.68	6.94	4.94	10.19	10.67	2.38	1.66	1.20	1.25
FEET	0.1299	0.97	0.43	0.27	0.07	0.07	0.22	0.15	0.24	0.26
CB		2.5	2.5	2.6						
TOTAL	1.8877	74.4	27.574	23.61	31.97	33.54	11.16	7.79	3.73	3.90

*CB = central blood

Table 2: Thermal Conductance between Compartments, Basal Metabolic Heat Production and Basal Blood Flow for Each Compartment.

SEGMENT (I)	COMPAERMENT (N)	TK(N) W/ ° C	MB(N) W	BFB(N) l/hr
HEAD 1	core	1.61	14.95	45
	muscle	13.25	0.12	0.12
	fat	16.1	0.13	0.13
	skin	0	0.1	1.44
THORAX 2	core	0.8	26.31	105
	muscle	2.77	2.9	3
	fat	11.54	1.24	1.28
	skin	0	0.23	1.05
ABDOMEN 3	core	0.8	26.31	105
	muscle	2.77	2.9	3
	fat	11.54	1.24	1.28
	skin	0	0.23	1.05
ARMS 4	core	1.4	0.82	0.84
	muscle	10.3	1.11	1.14
	fat	30.5	0.21	0.2
	skin	0	0.15	0.5
HANDS 5	core	6.4	0.09	0.1
	muscle	11.2	0.23	0.24
	fat	11.5	0.04	0.04
	skin	0	0.06	2
LEGS 6	core	10.5	2.59	2.69
	muscle	14.4	3.32	3.43
	fat	74.5	0.5	0.52
	skin	0	0.37	2.85
FEET 7	core	16.3	0.15	0.16
	muscle	20.6	0.02	0.02
	fat	16.4	0.05	0.05
	skin	0	0.08	3
TOTAL			86.45	285.13

Table 3: Values of Heat Transfer Coefficient for Each Segment

SEGMENT	HR W/M2.C	HC W/M2.C
HEAD	4.8	3.0
THORAX	4.8	2.1
ABDOMEN	4.8	2.1
ARMS	4.2	2.1
HANDS	3.6	4.0
LEGS	4.2	2.1
FEET	4.0	4.0

Table 4: Estimation of Distribution of Skin Receptors, Sweating, Vasodilatation and Vasoconstriction Command over the different Skin Areas.

SEGMENT	SKINR (I)	SKINS (I)	SKINV (I)	SKINC (I)
HEAD	0.21	0.081	0.132	0.01
THORAX	0.21	0.24	0.161	0.025
ABDOMEN	0.21	0.24	0.161	0.025
ARMS	0.1	0.154	0.095	0.19
HANDS	0.04	0.031	0.121	0.2
LEGS	0.2	0.219	0.23	0.2
FEET	0.03	0.035	0.1	0.35

Table 5: Estimates of Distribution of Heat Production in Muscle Compartment.

SEGMENT	WORKM (I)	CHILLM (I)
HEAD	0	0.02
THORAX	0.15	0.43
ABDOMEN	0.15	0.43
ARMS	0.08	0.05
HANDS	0.01	0
LEGS	0.6	0.07
FEET	0.01	0

Table 6: Temperature Set Point for initial condition.

SEGMENT	N	COMPARTMENT	TSET C
HEAD 1	1	core	36.96
	2	muscle	35.07
	3	fat	34.81
	4	skin	34.58
THORAX 2	5	core	36.89
	6	muscle	36.28
	7	fat	34.53
	8	skin	33.62
ABDOMEN 3	9	core	36.89
	10	muscle	36.28
	11	fat	34.53
	12	skin	33.62
ARMS 4	13	core	35.53
	14	muscle	34.12
	15	fat	33.59
	16	skin	33.25
HANDS 5	17	core	35.41
	18	muscle	35.38
	19	fat	35.3
	20	skin	35.22
LEGS 6	21	core	35.81
	22	muscle	35.3
	23	fat	35.31
	24	skin	34.1
FEET 7	25	core	35.14
	26	muscle	35.03
	27	fat	35.11
	28	skin	35.04
CENTRAL BLOOD	29		36.71

APPENDIX B

Programming 1: Simulation of Physiology Reaction in water immersion

Figure B.1 indicates step by step how the simulation of body temperature regulation in air and water environment is written by programming in FORTRAN .

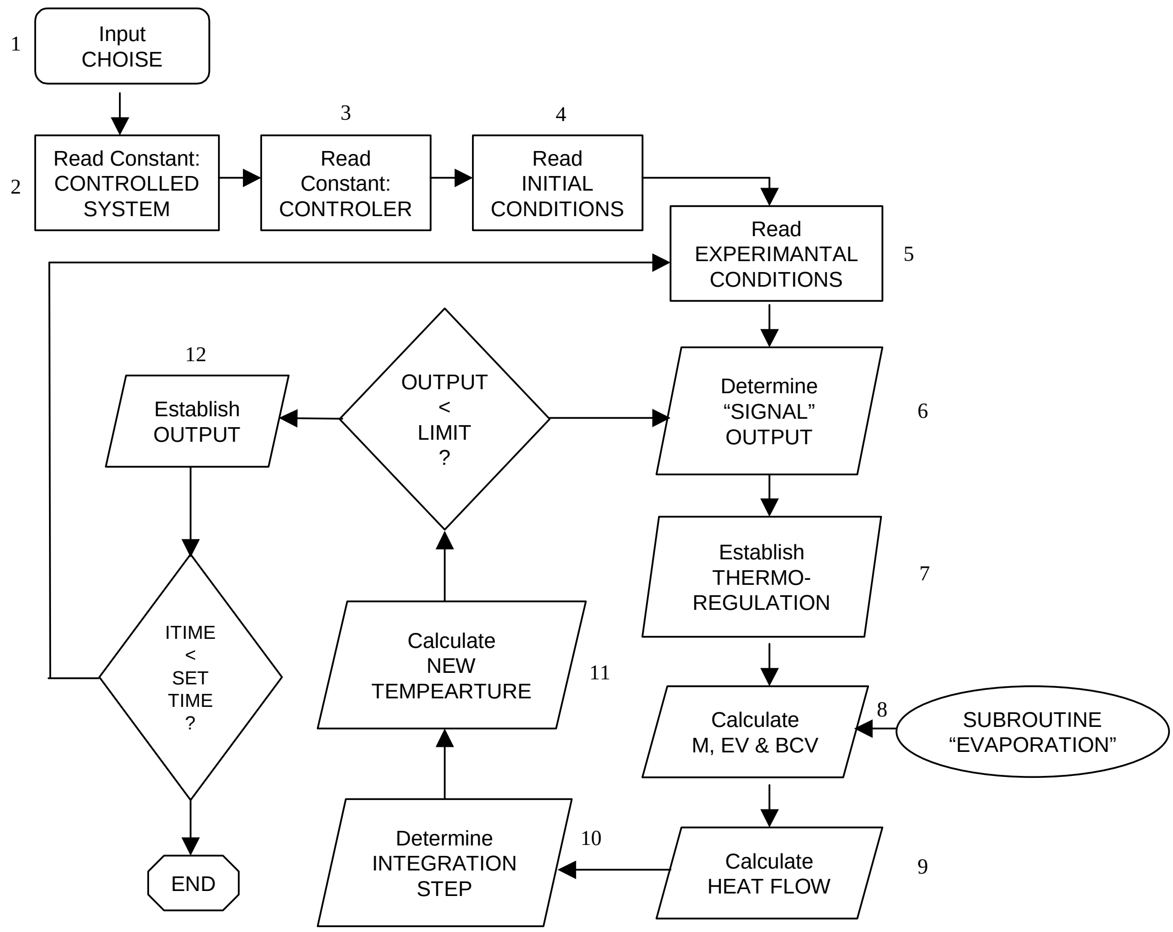

Figure B1 Flow Chart of Programming Steps

The first step is to select if the programming simulates water immersion with only head out or half body immersion. If (CHOICE=1) then simulation will do for water immersion with only head out whereas (CHOICE=2) for half body immersion.

The second section reads the constants as defined in the tables in Appendix A (Table 1,2 &3). The values of PV are taken from the Steam table and consist of the saturated water vapor pressure at 5°C intervals from 5°C to 50°C. As the same way, the third phase read the constants for controlling system as defined in the Table 4,5, & 6 (Appendix A). Table 6 shows the temperature set point, TSET, the value of steady-state equilibrium temperature which have reached the following conditions: air temperature 29.45°C, air velocity 0.1 m/s and relative humidity of 0.3.

The fourth step read the initial conditions for all compartment and set all elapsed time (TIME & ITIME) and rate of change of temperature in N to zero. The initial values for temperature of all compartments are set to those values of TSET.

The fifth step read the experimental conditions according to its environmental conditions. A loop is established here to run the program for 3 phases: 1. air environment, 2. water environment and 3. air environment again. The environmental conditions for air environment are air temperature (°C), air velocity (m/s), relative humidity (%), work rate (W) and intervals between output (INT). The value from work rate will be then used to calculate the total extra heat production in the working muscle by subtracting it from basal metabolic rate. Thus, WORK represents the total extra heat production in the working muscle. Next is to determine H(I), the total environmental heat transfer coefficient according to its environment: (MEDIA=100) for air environment and other for water environment. In water environment is further divided into water immersion with head out and half body immersion. Lastly, PAIR is calculated from the interpolation of PV according to the air temperature in experimental conditions.

In the sixth step, the output of “SIGNAL” will be determined by comparing the actual instantaneous temperature in all compartments with the set point temperature.

In the following step (seventh step), the thermoregulation of SWEAT, DILAT, CHILL and STRIC will be determined. Since the “SIGNAL” can be negative as well as positive, thus, the negative result of SWEAT, DILAT, CHILL and STRIC will then be set to zero.

In section 8, metabolic heat production, evaporative heat loss and blood flow fro each compartment in each section are calculated. Evaporative heat loss through skin will be different accordingly to the environmental media i.e. either air or water. Since evaporative heat loss through skin can not occur inside water immersion, only part of body which is expose to air environment will be considered for this heat loss. Evaporative heat loss is calculated in SUBROUINE “EVAPORATION”. In this subroutine, the water vapor pressure, PS and heat of vaporization of water, HFGSKIN at the skin surface temperature is read and interpolated from the steam table. If the computed evaporative heat loss, EVA is higher than maximum evaporative heat loss, EMAX, then EVA is set equal to EMAX.

Section 9 calculates the heat flow rate into or out of each of the compartments. Before that, BCV, the convective heat transfer between central blood and compartments. and TD, the conductive heat flow rate from each layer compartment to the next one are calculated. After this, all the heat flow rate component (M, EV, BCV & TD) are summed up for each compartment. In skin compartment where heat flow into or out from the surrounding environment, HF(N+3) is dependent on the environment media (air or water). Again, in the water environment, HF(N+3) is calculated differently for whole body immersion with head out and half body immersion. In water immersion, the evaporative heat loss through skin, E does not exist and the conductive heat transfer between skin layer and water (TW) instead of between skin layer and air (TAIR) in air environment.

In section 10 the optimum integration time step is determined. The initial value for the time increment is set to 1 min (0.01667 hr). Based on this increment, the temperature steps in each compartment are calculated, if any exceed 0.1°C, the time increment step, DT is reduced so that the maximum temperature change in any compartment is kept to 0.1 °C or less.

In section 11, new temperature is calculated based on the rate of change of temperature, F and time increment, DT. This is follow by testing if the clock exist the set interval between output, INT, If it is not exist, then the program return to the section “Determine SIGNAL output”, otherwise the program proceeds to the section 12, “ESTABLISH OUTPUT”.

In section 12, output such as total metabolic rate HP, and evaporative heat loss EVA is obtained by summing that of all compartments. Mean skin temperature, TS is calculated by summing of segmental skin temperatures. Net rate of heat storage, HFLOW for the whole body is obtained by summing all the heat flow over all compartments. HP, EVA, and HFLOW are reduced to W/m^2 by dividing them by the total body surface area SA. The calculation will then continue until ITIME is over the “SET TIME” in the section of “READ ENVIRONMENT CONDITIONS”.

```
      PROGRAM TEMPERATURE

      REAL,DIMENSION (29) :: T,TSET,RATE,QC,F,WARM,COLD,QF,SIGNAL
      REAL,DIMENSION (28) :: MB,BFB,TK,M,EV,BF,BCV,TD
      REAL,DIMENSION (10) :: PV
      REAL,DIMENSION(7) :: S,SKINR,SKIND,SKINC,WORKM,CHILM,HRD,HCV,H

!     Constant for controller
      REAL,PARAMETER::CSW=372.,SSW=33.7,PSW=0.,CDIL=136.,SDIL=17.,PDIL=0.
      REAL,PARAMETER::CCON=10.8,SCON=10.8,PCON=0.0,CCHIL=13.,SCHIL=0.4,PCHIL=1.0

      REAL,PARAMETER :: HW=105.0 !    by Rapp(1971)
      REAL :: LTIME
      INTEGER :: MEDIA,CHOICE

!     INPUT CHOISE: WHOLE OR HALF BODY IMMERSION

      PRINT*, "Enter 1 or 2 for the following choice"
      PRINT*, "1. Water immersion with head out"
      PRINT*, "2. Half Body water immersion"
      READ(*,*) CHOICE

!     READ CONSTANT FOR CONTROLLED SYSTEM

      OPEN (2,FILE='QC.DAT',STATUS='OLD')
      READ(2,'(1X,4F12.2)') QC
      CLOSE(2)

      OPEN (2,FILE='MB.DAT',STATUS='OLD')
      READ(2,'(1X,4F12.2)') MB
      CLOSE(2)

      OPEN (2,FILE='BFB.DAT',STATUS='OLD')
      READ(2,'(1X,4F12.2)') BFB
      CLOSE(2)

      OPEN (2,FILE='TK.DAT',STATUS='OLD')
```

```
READ(2,'(1X,4F12.2)') TK
CLOSE(2)

OPEN (2,FILE='S.DAT',STATUS='OLD')
READ(2,'(1X,1F12.4)') S
CLOSE(2)

OPEN (2,FILE='HRD.DAT',STATUS='OLD')
READ(2,'(1X,1F12.1)') HRD
CLOSE(2)

OPEN (2,FILE='HCV.DAT',STATUS='OLD')
READ(2,'(1X,1F12.1)') HCV
CLOSE(2)

OPEN (2,FILE='PV.DAT',STATUS='OLD')
READ(2,'(1X,1F12.2)') PV
CLOSE(2)

SA=0.
DO I=1,7
SA=SA+S(I)
END DO

READ CONSTANT FOR THE CONTROLLER

OPEN (2,FILE='TSET.DAT',STATUS='OLD')
READ(2,'(1X,4F12.2)') TSET
CLOSE(2)

OPEN (2,FILE='RATE.DAT',STATUS='OLD')
READ(2,'(1X,4F12.2)') RATE
CLOSE(2)

OPEN (2,FILE='SKINR.DAT',STATUS='OLD')
READ(2,'(1X,1F12.3)') SKINR
CLOSE(2)
```

```
      OPEN (2,FILE='SKIND.DAT',STATUS='OLD')
      READ(2,'(1X,1F12.3)') SKIND
      CLOSE(2)

      OPEN (2,FILE='SKINC.DAT',STATUS='OLD')
      READ(2,'(1X,1F12.3)') SKINC
      CLOSE(2)

      OPEN (2,FILE='WORKM.DAT',STATUS='OLD')
      READ(2,'(1X,1F12.3)') WORKM
      CLOSE(2)

      OPEN (2,FILE='CHILM.DAT',STATUS='OLD')
      READ(2,'(1X,1F12.3)') CHILM
      CLOSE(2)

!     READ INITIAL CONDITIONS

      OPEN (1,FILE='RESULT.TXT',STATUS='OLD')
      WRITE(1,'(1X,"TIME          SH        M         EV         TS         TR")')

      OPEN (2,FILE='T.DAT',STATUS='OLD')
      READ(2,'(1X,4F12.2)') T
      CLOSE(2)

      TIME=0.
      ITIME=0
      DO N=1,29
      F(N)=0.
      END DO

!      READ EXPERIMENT CONDITIONS

10    IF (ITIME<11) THEN
         MEDIA=100 ! For Air Environment
         OPEN (2,FILE='EXPERIMENT1.DAT',STATUS='OLD')
```

```
    READ(2,'(1X,4F12.2,I4)') TAIR,V,RH,WORK,INT
    CLOSE(2)
ELSEIF (ITIME<26) THEN
    MEDIA=200 ! For Water Environment
    OPEN (2,FILE='EXPERIMENT2.DAT',STATUS='OLD')
    READ(2,'(1X,5F12.2,I4)') TAIR,V,RH,TW,WORK,INT
    CLOSE(2)
ELSEIF (ITIME<56) THEN
    MEDIA=100
    OPEN (2,FILE='EXPERIMENT3.DAT',STATUS='OLD')
    READ(2,'(1X,4F12.2,I4)') TAIR,V,RH,WORK,INT
    CLOSE(2)
ELSE
STOP
ENDIF

IF (WORK-86.5<0) THEN
    WORK=0.
ELSE
    WORK=(WORK-86.5)*0.78
ENDIF

IF (MEDIA==100) THEN
    DO I=1,7
            H(I)=(HRD(I)+3.16*HCV(I)*V**0.5)*S(I)
    END DO
ELSE
    PART0 : SELECT CASE (CHOICE)
            CASE (1) ! water immersion wtih head out
                    H(1)=(HRD(1)+3.16*HCV(1)*V**0.5)*S(1)
                    DO I=2,7
                    H(I)=HW*S(I)
                    END DO
            CASE (2) ! half body water immersion
                    DO I=1,2
                    H(I)=(HRD(I)+3.16*HCV(I)*V**0.5)*S(I)
                    END DO
```

```
                  DO I=4,5
                  H(I)=(HRD(I)+3.16*HCV(I)*V**0.5)*S(I)
                  END DO
                  H(3)=HW*S(3)
                  DO I=6,7
                  H(I)=HW*S(I)
                  ENDDO
       END SELECT PART0
     ENDIF

     I=TAIR/5
     PAIR=RH*(PV(I)+(PV(I+1)-PV(I))*(TAIR-5*I)/5.)

!    DETERMINE "SIGNAL" OUTPUT

100   DO N=1,29
       WARM(N)=0.
       COLD(N)=0.
       SIGNAL(N)=T(N)-TSET(N)+RATE(N)*F(N)

       IF (SIGNAL(N)<0) THEN
             COLD(N)=-SIGNAL(N)
       ELSE
             WARM(N)=SIGNAL(N)
       ENDIF
     END DO

!    ESTABLISH THERMOREGULATION

     WARMS=0.
     COLDS=0.
     DO I=1,7
       K=4*I
       WARMS=WARMS+WARM(K)*SKINR(I)
       COLDS=COLDS+COLD(K)*SKINR(I)
     END DO
```

```
SWEAT=CSW*SIGNAL(1)+SSW*(WARMS-COLDS)+PSW*WARM(1)*WARMS
DILAT=CDIL*SIGNAL(1)+SDIL*(WARMS-COLDS)+PDIL*WARM(1)*WARMS
CHILL=(CCHIL*SIGNAL(1)+SCHIL*(COLDS-WARMS))+PCHIL*(WARMS-COLDS)
STRIC=-CCON*SIGNAL(1)-SCON*(WARMS-COLDS)+PCON*COLD(1)*COLDS

IF (SWEAT<0) THEN
    SWEAT=0.
END IF
IF (DILAT<0) THEN
    DILAT=0.
END IF
IF (STRIC<0) THEN
    STRIC=0.
END IF
IF (CHILL<0) THEN
    CHILL=0.
END IF

!       CALCULATE M,EV AND BF

DO I=1,7
    N=4*I-3
    M(N)=MB(N)
    EV(N)=0.
    EV(5)=(86.4+WORK)*0.0026749*(44.-PAIR)
    BF(N)=BFB(N)

    M(N+1)=MB(N+1)+WORKM(I)*WORK+CHILM(I)*CHILL
    EV(N+1)=0.
    BF(N+1)=BFB(N+1)+M(N+1)-MB(N+1)

    M(N+2)=MB(N+2)
    EV(N+2)=0.
    BF(N+2)=BFB(N+2)

    M(N+3)=MB(N+3)
    BF(N+3)=(BFB(N+3)+SKIND(I)*DILAT)/(1.+SKINC(I)*STRIC)
```

```
      END DO

      IF (MEDIA==100) THEN
         DO I=1,7
            N=4*I-3
            CALL EVAPORATION (I,T(N+3),PAIR,H(I),SWEAT,TSET(N+3),EV(N+3))
            END DO
      ELSE
         PART1: SELECT CASE (CHOICE)
            CASE (1) ! water immersion wtih head out
                  I=1
                  N=4*I-3
                  CALL EVAPORATION (I,T(N+3),PAIR,H(I),SWEAT,TSET(N+3),EV(N+3))
                  DO I=2,7
                  EV(4*I)=0.
                  END DO
            CASE (2) ! half body water immersion
                  DO I=1,2
                        N=4*I-3
                  CALL EVAPORATION (I,T(N+3),PAIR,H(I),SWEAT,TSET(N+3),EV(N+3))
                  END DO
                  DO I=4,5
                        N=4*I-3
                  CALL EVAPORATION(I,T(N+3),PAIR,H(I),SWEAT,TSET(N+3),EV(N+3))
                  END DO
                  EV(3)=0.
                  DO I=6,7
                  EV(4*I)=0.
                  ENDDO
         END SELECT PART1
      ENDIF

!    CALCULATE HEAT FLOWS

      DO K=1,28
         BCV(K)=BF(K)*(T(K)-T(29))
         TD(K)=TK(K)*(T(K)-T(K+1))
```

```
END DO

DO I=1,7
    K=4*I-3
    QF(K)=M(K)-EV(K)-BCV(K)-TD(K)
    QF(K+1)=M(K+1)-BCV(K+1)+TD(K)-TD(K+1)
    QF(K+2)=M(K+2)-BCV(K+2)+TD(K+1)-TD(K+2)
ENDDO

IF (MEDIA==100) THEN
    DO I=1,7
              K=4*I-3
              QF(K+3)=M(K+3)-BCV(K+3)-EV(K+3)+TD(K+2)-H(I)*(T(K+3)-TAIR)
    END DO
ELSE
    PART2 : SELECT CASE (CHOICE)
          CASE (1) ! water immersion wtih head out
          QF(4)=M(4)-BCV(4)-EV(4)+TD(3)-H(1)*(T(4)-TAIR)
           DO I=2,7
                K=4*I-3
                QF(K+3)=M(K+3)-BCV(K+3)+TD(K+2)-H(I)*(T(K+3)-TW)
           ENDDO
           CASE (2) ! half body immersion
           DO I=1,2
                K=4*I-3
                QF(K+3)=M(K+3)-BCV(K+3)-EV(K+3)+TD(K+2)-H(I)*(T(K+3)-TAIR)
           END DO
           DO I=4,5
                K=4*I-3
                QF(K+3)=M(K+3)-BCV(K+3)-EV(K+3)+TD(K+2)-H(I)*(T(K+3)-TAIR)
          END DO
                QF(12)=M(12)-BCV(12)+TD(11)-H(3)*(T(12)-TW)
          DO I=6,7
                K=4*I-3
                QF(K+3)=M(K+3)-BCV(K+3)+TD(K+2)-H(I)*(T(K+3)-TW)
           ENDDO
   END SELECT PART2
```

```
      ENDIF

      QF(29)=0.
      DO K=1,28
         QF(29)=QF(29)+BCV(K)
      END DO
      QF(29)=QF(29)-0.08*WORK

!     DETERMINE OPTIMUM INTEGRATION STEP

      DT=0.016666667
      DO K=1,29
         F(K)=QF(K)/QC(K)
         U=ABS(F(K))
         IF (U*DT-0.1>0) THEN
                  DT=0.1/U
         END IF
      END DO

!     CALCULATE NEW TEMPERATURE

      OPEN (3,FILE='TEMP.TXT',STATUS='OLD')

      DO K=1,29
         T(K)=T(K)+F(K)*DT
      END DO

      CLOSE(3)

      TIME=TIME+DT
      LTIME=60.*TIME

      IF (LTIME-INT-ITIME<0) THEN
         GOTO 100
      ENDIF

!     ESTABLISH OUTPUT
```

```
ITIME=ITIME+INT

HP=0.
EVA=0.
TS=0.
HFLOW=0.

DO N=1,28
   HP=HP+M(N)
   EVA=EVA+EV(N)
ENDDO

EVA=EVA+0.08*WORK

DO I=1,7
   TS=TS+T(4*I)*QC(4*I)/3.90
ENDDO

DO N=1,29
   HFLOW=HFLOW+QF(N)
ENDDO

EVA=EVA/SA
HP=HP/SA
HFLOW=HFLOW/SA

WRITE(1,'(1X,I4,5F8.2)')ITIME,HFLOW,HP,EVA,TS,T(5)

GOTO 10

CLOSE(1)


END PROGRAM TEMPERATURE
```

```
SUBROUTINE EVAPORATION (J,TSKIN,PRAIR,HEVN,SW,TEMSET,EVAP)

          REAL,DIMENSION (10) :: PV,HFG
          REAL,DIMENSION (7) :: HRD,S,SKINS
          OPEN (2,FILE='PV.DAT',STATUS='OLD')
          READ(2,'(1X,1F12.2)') PV
          CLOSE(2)

          OPEN (2,FILE='HRD.DAT',STATUS='OLD')
          READ(2,'(1X,1F12.1)') HRD
          CLOSE(2)

          OPEN (2,FILE='S.DAT',STATUS='OLD')
          READ(2,'(1X,1F12.4)') S
          CLOSE(2)

          OPEN (2,FILE='SKINS.DAT',STATUS='OLD')
          READ(2,'(1X,1F12.3)') SKINS
          CLOSE(2)

          OPEN (2,FILE='HFG.DAT',STATUS='OLD')
          READ(2,'(1X,4F12.2)') HFG
          CLOSE(2)

          K=TSKIN/5
          PS=PV(K)+(PV(K+1)-PV(K))*((TSKIN-5*K)/5.)
          EMAX=(PS-PRAIR)*2.14*(HEVN-HRD(J)*S(J))
          ES=SKINS(J)*SW*2.**((TSKIN-TEMSET)/4.)
          HFGSKIN=HFG(K)+(HFG(K+1)-HFG(K))*(TSKIN-5*K)/5.
          ED=(PS-PRAIR)*HFGSKIN*S(J)*(1.6944*10.**(-4.))
          EVAP=ES+ED-(ES*ED/EMAX)
                    IF(EVAP>EMAX) THEN
                              EVAP=EMAX
                    END IF

END SUBROUTINE EVAPORATION
```

Programming 2: Conversion Volt to Celsius

```
      PROGRAM TERMOCOUPLE

!  This is a programming to convert volt from digital recoerder to temperature in calsius
      PARAMETER(K=3660)
      INTEGER, DIMENSION (1,K) :: H
      REAL, DIMENSION (7,K) :: G
      INTEGER, DIMENSION (7,K) :: E
      REAL, DIMENSION (7,K) :: S

      OPEN(1,FILE="VOLTAN.DAT",STATUS="OLD")    ! This is data from digital recoerder
      OPEN(2,FILE="TEMVSVOL.DAT",STATUS="OLD")  ! The converted temperature will
wirte in this file

      DO M=1,K,1
      READ(1,"(I4,2X,F7.5,2X,F7.5,2X,F7.5,2X,F7.5,2X,F7.5,2X,F7.5,2X,F7.5)")H(1,M),G(1,M
),G(2,M),G(3,M),G(4,M),G(5,M),G(6,M),G(7,M)
      ENDDO

! The thermocouple offset and multiple 1000 for conversion in amplifier
      N=1
            DO M=1,K,1
            E(N,M)=(G(N,M)-0.0302)*1000
            ENDDO
      N=2
            DO M=1,K,1
            E(N,M)=(G(N,M)+0.0233)*1000
            ENDDO
      N=3
            DO M=1,K,1
            E(N,M)=(G(N,M)+0.0037)*1000
            ENDDO
      N=4
            DO M=1,K,1
            E(N,M)=(G(N,M)-0.0018)*1000
```

```
        ENDDO
N=5
        DO M=1,K,1
        E(N,M)=(G(N,M)-0.0002)*1000
        ENDDO
N=6
        DO M=1,K,1
        E(N,M)=(G(N,M)-0.0025)*1000
        ENDDO
N=7
        DO M=1,K,1
        E(N,M)=(G(N,M)+0.0078)*1000
        ENDDO

DO N=1,7,1
DO M=1,K,1

t1=0.
t2=50.
t3=(t1+t2)/2.

100     F1=F(t1)
F2=F(t2)
F3=F(t3)

IF ((F2-F3) ==(F3-F1)) THEN

TEMPERATURE: SELECT CASE (N)
        CASE (1)
        S(1,M)=t1
        CASE (2)
        S(2,M)=t1
        CASE (3)
        S(3,M)=t1
        CASE (4)
        S(4,M)=t1
        CASE (5)
```

```
        S(5,M)=t1
        CASE (6)
        S(6,M)=t1
        CASE (7)
        S(7,M)=t1
    END SELECT TEMPERATURE

    ELSEIF ((F2-E(N,M))<(E(N,M)-F1)) THEN
    t1=t3
    t2=t2
    t3=(t1+t2)/2.
    GOTO 100
    ELSE
    t1=t1
    t2=t3
    t3=(t1+t2)/2.
    GOTO 100
    ENDIF

    ENDDO
    ENDDO

    DO M=1,K,60
    TS=0.07*S(1,M)+0.175*S(2,M)+0.175*S(3,M)+0.14*S(4,M)+0.05*S(5,M)+0.39*S(6,M)
    WRITE(2,"(2F8.1)") S(7,M),TS

!   S(7,M) is the core temperature and TS is mean skin temperature.

    ENDDO

    ClOSE(1)
    CLOSE(2)

    END PROGRAM TERMOCOUPLE
```

```
REAL FUNCTION F(t) ! This function calculate the formula for Copper-Thermocouple

REAL,PARAMETER::b0=-1.8533063273*10.,b1=3.8918344612*10.,b2=1.6645154356*10.**-2
REAL,PARAMETER::b3=-7.8702374448*10.**-5,b4=2.2835785557*10.**-7, b5=-3.5700231258*10.**-10
REAL,PARAMETER::b6=2.9932909136*10.**-13,b7=-1.2849848798*10.**-16, b8=2.2239974336*10.**-20

F=(b0*t**0)+(b1*t**1)+(b2*t**2)+(b3*t**3)+(b4*t**4)+(b5*t**5)+(b6*t**6)+(b7*t**7)+
(b8*t**8)+125.*EXP((-1./2.)*(((t-127.)/65.)**2))

END FUNCTION F
```

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修士　論文

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