1-1-1975

Thermal Regulation of the Human Body

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THERMAL REGULATION OF THE HUMAN BODY

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THERMAL REGULATION OF THE HUMAN BODY

The supervision of the complicated task of managing your body's energy resources is laid to many ingenious systems, both chemical and physical, in your body. One group of such control systems keeps the temperature of the body relatively stable despite a wide range of variety and intensity of the energy conversion and utilization processes which occur there.

For example, increase in thermal stimulation of body temperature sensors may result in secretion of water by the sweat glands which in turn cools the skin surface and increases the heat outflow. In another scenario, thermal stimulation can initiate stricturing of certain blood vessels, for example in the extremeties. This shifts the blood flow pattern to levels more removed from the skin's surface, thereby increases the effective thickness of the heat conduction barrier, the body's skin, and maintains interior temperature.

It is by the suitable combination of such unconscious activities, combined with our own efforts which are prompted by consciousness of thermal comfort, that our body temperature is held fixed. The purpose of this module is to explore this regulating system.

EXPLORATIONS IN THINKING

The innumerable hours of your life which have been whiled away thinking about the weather, or more particularly about your sense of "thermal" comfort, establish a significance for it with you. However, the character of these concerns belies their true import; for it is survival and not comfort which is involved in the maintenance of a steady and proper body temperature.

Recall some of your experiences. When it is cold you: put on layers of clothing; avoid going outside with your hair wet; rub your hands; drink hot buttered rum; shelter yourself from the wind; direct your feet to the sunny side of the street. When it is hot you: take off your clothes; wear porous clothing; fan yourself; sweat; find the breeze; lie still; drink cold beer; find the shade; jump into a pool; pant. Each of these activities relates to one or more of the fundamental thermal energy transport processes of conduction, convection, radiation, and evaporation. Try to classify these activities according to these process categories. Can you recall other activities, not mentioned here, and so classify them?

EXPLORATION IN DOING

1) Temperature Regulation within the Body Interior.

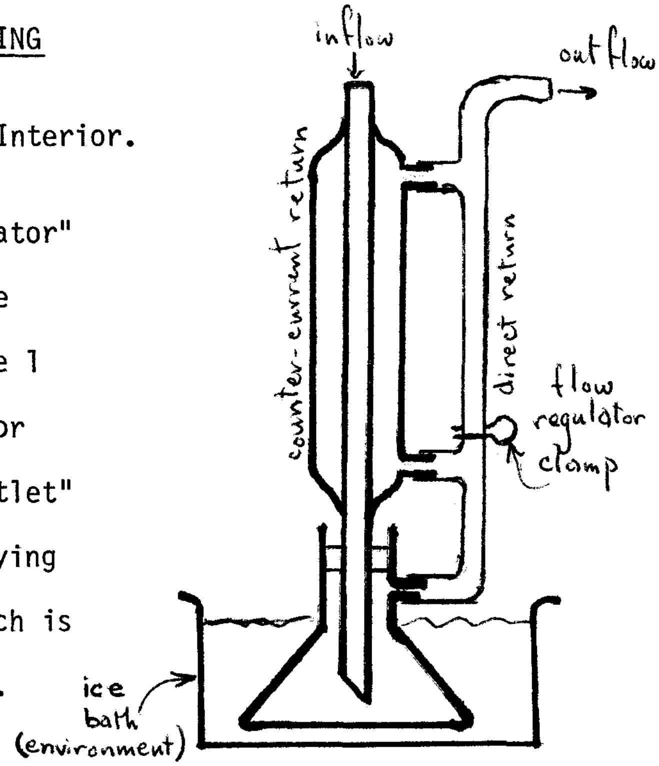


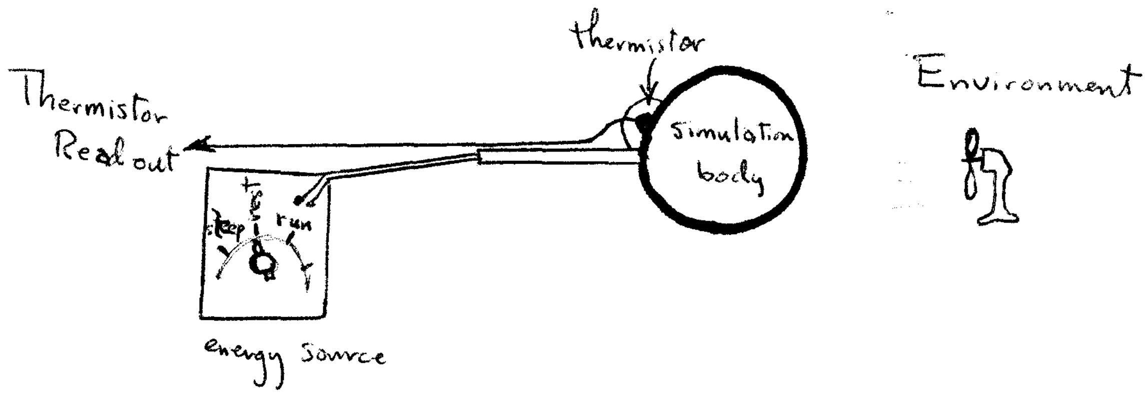
Figure 1: Countercurrent heat exchange simulator.

Play the role of the "temperature regulator" by operating the countercurrent heat exchange simulator. This system is depicted in Figure 1 (to the right). The object here is to monitor and record the "end" temperature and the "outlet" temperature of the circulating water for varying amounts of countercurrent recirculation (which is controlled by means of the adjustable clamp).

2) Temperature Regulation on the Body Surface.

Finally, play the role of "temperature regulator" by manning environmental elements, (i.e., the fan, water spray, clothes, and candle) in conjunction with the simulation body (ball). First, set the energy source control to "rest". Start with the simulation body (ball) in some steady temperature state where it is hotter than its environment. At this point, the body should be clothed. Note the temperature, since it is this value which you shall have to maintain. Set the source to "mild work." Then, use any or all of the environmental elements to endeavor to maintain the simulation body temperature steady at its original value. How are you doing? Try other energy source levels (e.g. running) and attempt to similarly maintain the body temperature at the original level.

List some of the difficulties of achieving this control, and discuss them with a partner. Then write a brief congratulatory "Ode to the Noble Hypothalmus" for doing so well as the controller in our bodies.



INVENTION

A. Prerequisites

Before you begin this module, you should be able to:

1. Evaluate heat flow in systems involving the four major thermal energy transport mechanisms (conduction, convection, radiation, evaporation).

2. Describe qualitatively the function of each of these four thermal transport mechanisms at the body surface and relate appropriate environmental conditions to the dominance of one or another of these mechanisms with respect to temperature regulation of the body.

3. Write, and use to evaluate process energies, the total energy balance equation for a given body in a given environment.

B. Objectives

After you have completed this module, you will be able to:

1. Qualitatively describe the internal mechanisms (e.g. vascular constriction, countercurrent heat exchange, shivering, etc.) used by the body to regulate its temperature.

2. Utilize a standard surface heat transfer table and the standard heat exchange laws to evaluate the contribution of each of the external (surface) heat exchange mechanisms to the total temperature regulation effort of the body.

3. Recognize and describe the performance of a feedback mechanism which is capable of maintaining a steady system temperature.

C. References

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D. Countercurrent Heat Exchange

The mechanisms of thermal energy production and control involved in body temperature regulation and already discussed are: surface convection, conduction, radiation, and evaporation; internal blood circulation (i.e., forced convection); metabolism. In addition to these there is a somewhat subtle combination of convection and conduction which is exploited by certain types of blood circulation routes which bears special mention and description. It is called counter-current heat exchange.

To understand why it is effective, we must digress a bit about a general strategy of temperature regulation employed in the body. Generally speaking, the body preserves steady core temperature at the price of allowing skin surface temperatures to vary widely, depending upon circumstances of environment and work demand. It is useful (if not strictly complete) to look upon this as coming about principally by control of the temperature gradient between core and skin surface. This means that not merely the skin/core temperature difference, but the sharpness of that temperature gradation (i.e., the thickness of the temperature transition region) is significant in determining the rate of outward heat flow.

The flow of blood through the arteries (and return through the veins) sets an effective level below the skin surface where the temperature is that of the core. Obviously the rate of flow has much to do with where this level lies as does the location of the blood vessels with respect to the surface. What is more subtle is that the disposition of blood vessels with respect to one another (arteries with respect to veins) can play a major role in determining the pattern of heat flow in the temperature transition region. Counter-current heat exchange exploits such a specialized positioning and, as such, is a striking example of how the interplay of conduction and convection can bring about a favorable adjustment in the sharpness of the core/surface temperature gradient. This is now described.

Consider the flow system utilized in the Exploration activity #1. It may be schematically represented by the simplified diagram in Figure 2 below which facilitates explanation of the functioning of such a system. The key point is that heat conduction may take place through the (common) separating wall between input and output flow paths. This process will tend to equalize

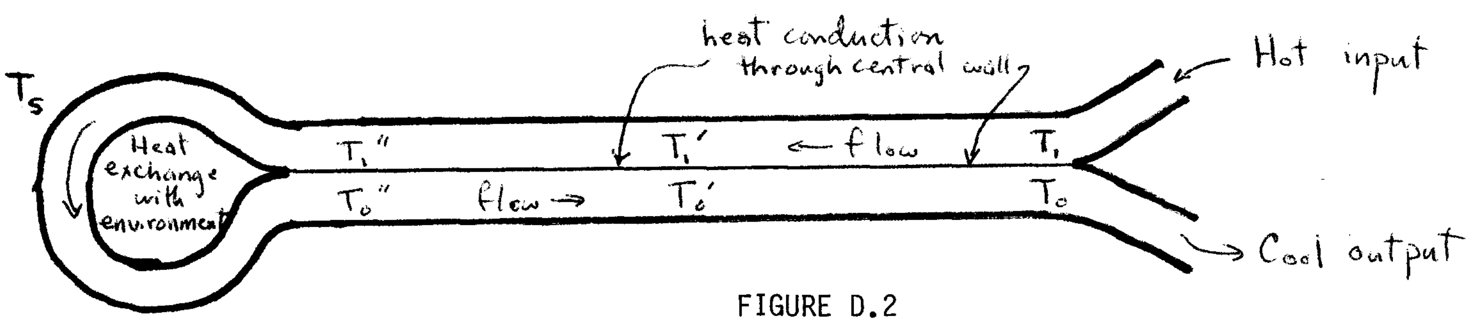


FIGURE D.2
Simplified counter-current heat exchange.

the temperatures of the liquids in adjacent sections (across that wall). Thus $T_1 = T_0$; $T_1' = T_0'$; $T_1'' = T_0''$.

But in any case, the liquid just returning from the environmental heat exchange section must be at the extreme (lowest) temperature of the entire flow system, say T_s. Thus $T_0'' = T_s$. At the same time the incoming liquid must be at nearly the core temperature, say T_b. Thus $T_1 = T_b$. Some simple logic should convince you that all of these requirements can be met only it the temperature change $T_b \rightarrow T_s$ takes place gradually along the whole length of the double-path portion of the flow route.

In the absence of the conduction between the input and output paths, the pure convective character of the flow efficiently transports heat directly from the core to the environmental "end;" thus, $T_1'' = T_1$ would then be true. The "end" temperature T_s would consequently be higher than our former case, and more heat exchange (thermal energy loss) would occur with (to) the environment. Consequently, T_0'' would be considerably less than T_1'' and $T_0'' = T_0$. This means that the liquid would return to the core much colder than formerly.

A close scrutiny of this reasoning will show that, in the case of counter-current heat exchange, part of the core's thermal energy which would ordinarily be transported to the end and lost to the environment is, instead, returned to the core by the returning liquid, having first been "conducted" across the common wall between the flow paths.

How does this work in a real body? Consider the blood flow in a human arm. Figure (3) shows the main circulatory routes for an environmental temperature of 10°C and 30°C. Blood is supplied by deep, major arteries at a temperature of about 37°C. Blood which returns to the heart may be routed by way of deep veins which run in close contact with the supply arteries and/or by way of veins located just below the surface of the skin.

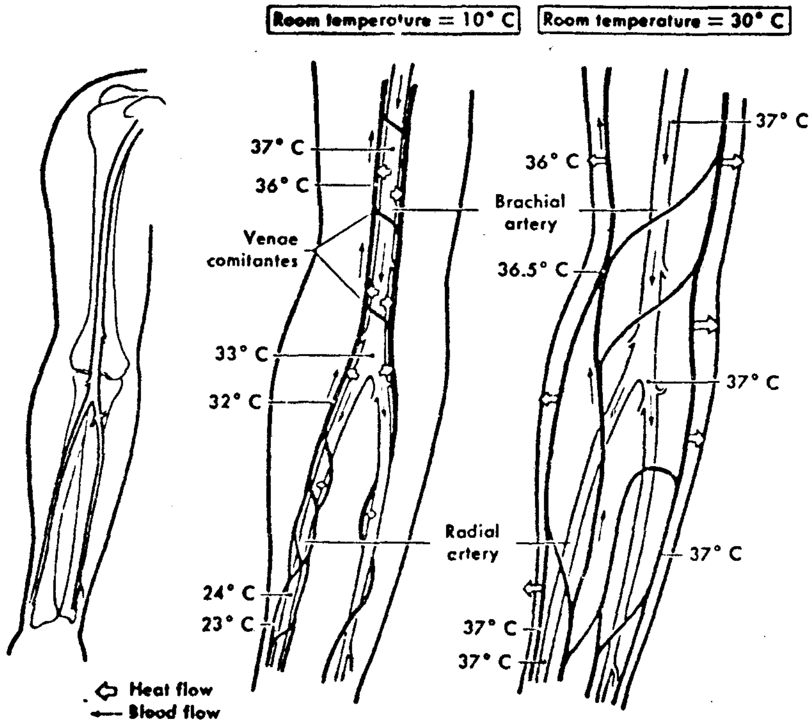


FIGURE D.3
Counter current heat exchange with human arm for two environmental temperatures, 10°C and 30°C. (Reference 5, page 103)

In a cold environment most of the return flow is by way of deep routed veins. This maximizes the undercurrent heat exchange and the cool returning blood is warmed by the incoming arterial blood. Thus not only does the skin temperature go down, but the temperature change to the interior is made more gradual (i.e. the temperature gradient across the skin is reduced). In this way external loss of thermal energy is minimum since conductance is low. Note that blood is supplied to the arm at 37°C and returns to the heart at 36°C. Review your data from Exploration exercise #1 in the light of these concepts.

On the other extreme, in a warm environment, the major blood return route is by veins running close to the skin surface. This blood is cooled as heat flow is conducted to cool body tissue near the surface of the skin. Thus excess core thermal energy is carried to the skin's surface where it may be lost through one of the heat flow mechanisms.

E. Regulation of Body Temperature.

Each of the body mechanisms involving thermal energy production or dissipation which have been discussed are interrelated to provide constant body temperature. The class of animals, including humans, that maintain a constant body temperature are called homeotherms (warm-blooded animals). Animals not possessing the necessary thermo-regulation system for a constant body temperature are called poikilotherms (cold-blooded animals). The body temperature of poikilotherms varies with their environmental temperature. Reptiles are examples of poikilotherms.

The exploration activity #2 has provided you with some first hand experience at being a thermal regulator. The regulation of body temperature in humans is also analogous to the temperature regulation system used in home heating. As Figure (4) illustrates, the central regulating device of the home heating system is the thermostat. This device is sensitive to changes which occur in the interior temperature and regulates hot or cold air flow into the rooms of the home. Heat transfer occurs between the house and its environment by conduction, convection, and radiation. Thus, additional heating or cooling is required to maintain the stable (pre-set) temperature as determined by the thermostat regulator.[**]

[**] See module series "At Home with Heat," module 5, page 5-1.

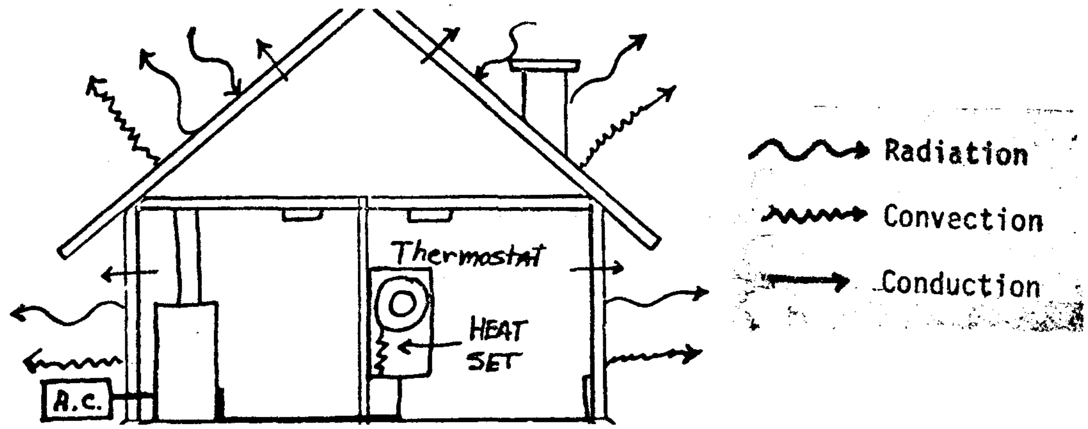


FIGURE D.4
A home heating unit regulated by a thermostat provides heating and cooling to maintain a constant temperature environment.

The main temperature regulating device for the regulation of human body temperature is the hypothalamus. This organ, located near the center of the brain just above the spinal cord, is connected through the nerves to the thermal sensors on the body surface and in the body core. Like the thermostat, it controls the heat regulating mechanisms for maintaining the pre-set temperature of 37°C. Figure (5) shows a schematic diagram which illustrates the relationship between the major elements of the human temperature regulating system.

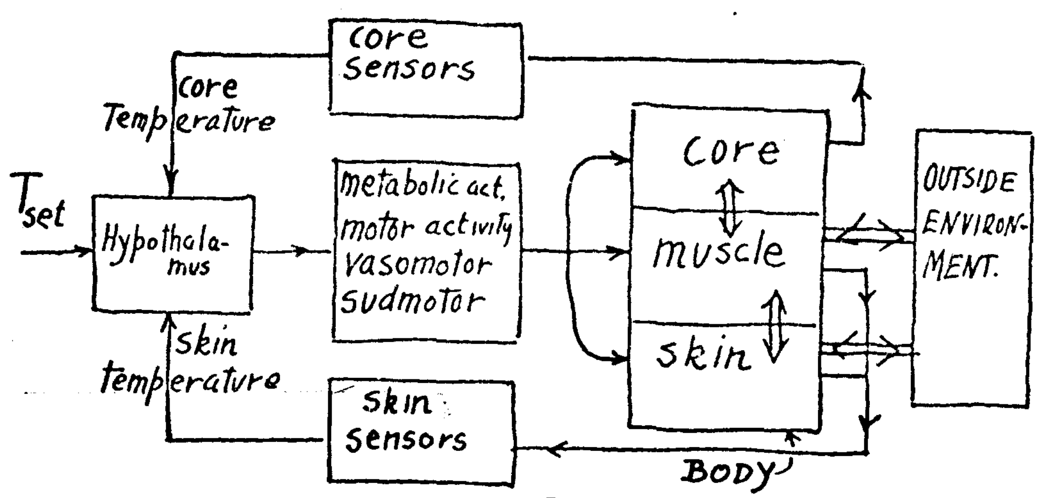


FIGURE D.5
Diagram showing the main parts of the human body temperature regulation. (Reference 5, page 6-106)

To maintain a constant core temperature, the body utilizes one or several mechanisms. The choice of mechanism by the body in response to changes in environmental temperature varies depending upon the nature of the conditions. However, the result is always that the core temperature is maintained under rigid control but skin temperature is allowed to vary over a wide range of temperature.

The following specific mechanisms are utilized by the body to maintain the core temperature:

A. Increased metabolic rate

B. Increased motor activity (shivering)

C. Reduction of heat flow from the core to outer extremeties by restriction of blood flow carrying thermal energy from the core to the skin.

D. Increased blood flow from the core to the outer extremities which carries thermal energy from the core to the skin.

E. Increasing the sweat produced by the eccrine glands thus cooling the skin by evaporation.

Processes A through C are used to <u>sustain</u> core temperature while processes D and E <u>restrain</u> it.

The summative effects of the mechanisms for heating and cooling can be estimated by using the First Law of Thermodynamics in the form of a rate equation as

$$\text{metabolic rate} = \begin{array}{c}\text{rate of heat exchange}\\ \text{with the environment}\end{array} + \text{mechanical power} \qquad (D.1)$$

For a body which exchanges thermal energy with its environment, the mechanisms of Radiation (H_R), Conduction (H_d), Convection (H_V), can carry thermal energy into or away from the body. Evaporation (H_E) can only carry energy from the body. Thus, equation (1) for a body at constant temperature becomes

$$M = H_v + H_R + H_d + H_E + P \tag{D.2}$$

where

M = rate of metabolism

$(H_v + H_R + H_d)$ = rate of heat transfer by the body by convection (H_v), radiation (H_R), and conduction (H_d).

H_E = rate of heat lost through evaporation.

P = rate of doing mechanical work.

Equation (2) expresses the energy balance for a body at constant temperature. If the temperature is NOT constant, the body will be retaining thermal energy (temperature rising) or relinquishing thermal energy (temperature decreasing). Equation (2) in either case would require an additional negative term on the left hand side. In this case, one has R for the thermal energy retention rate and

$$M - R = H_v + H_R + H_d + H_E + P \tag{D.3}$$

In sections (E) and (G) of the module FUNDAMENTAL ENERGY PROCESSES OF THE BODY, specific relations for the terms in equations (2) and (3) have been presented. They are as follows:

$$H_v = K_v A_{body} (T_s - T_a) \tag{G.8}$$

$$H_R = (5.67 \times 10^{-8}) A_{body} (T^4_{body} - T^4_{walls}) \tag{G.11}$$

$$H_d = \frac{K_s K_m}{K_s + K_m} \left(\frac{T_b - T_m}{x}\right) \tag{G.17}$$

$$P = \frac{F \times d}{t} \tag{E.6c}$$

These individual expressions inserted into equation (2) will give the approximate quantitative relationship for heat regulation in the human body. Experimental investigations of temperature regulation have been performed. Some results of these experiments are given in Table (1).

Conditions	Air Temperature °C	Wall Temperature °C	Percent Thermal Energy Lost By Evaporation	Radiation	Convection
Body and air at rest	16.0	49.1	21	*	79
Body and air at rest	17.1	19.0	10	40	50
Body and air at rest	29.4	52.4	78	*	22
Body and air at rest	35.4	36.6	100	0	0
Body at rest Air movement 264 cm/sec	22.8	22.8	17	13	70

*in these cases, thermal energy is inputted to the body through radiative heat exchange.

TABLE D.1
Percent thermal energy lost from a human body surface under various environmental temperature conditions.

Although no general relationship exists for determining the percentage of heat flow in any specific situation, Table (1) does suggest how to approximate the energy lost through each avenue in a variety of situations.

EXERCISE D.1

1. Consider the data from the second line of Table (1) and assume a skin temperature T_s = 32°C. Find the total rate of thermal energy lost per area from the body in watts/m^2.
2. Assuming that this subject is resting quietly at a basal metabolic rate of 90 watts, find the rate at which the body is relinquishing thermal energy.

Solutions are given on the next page.

EXERCISE D.1 SOLUTIONS AND/OR SUGGESTIONS

1. $H_R = (5.67 \times 10^{-8})\ A\ (T_b^4 - T_w^4) = h_R A$

   $h_R = (5.67 \times 10^{-8})\ (310^4 - 304^4)$

   $= 78.4$ watts/m^2

   Since radiation accounts for 40% of the total loss,

   $h = h_R/0.4 = \frac{78.4}{0.4}$

   $h = 196$ w/m^2

2. $M - R = H_v + H_d + H_R + H_E + P$, where R = net thermal energy retained.

   From above

   $H = hA = H_v + H_d + H_R + H_E$

   $= (196 \text{ watts/m}^2)\ (1.8 \text{ m}^2) = 353$ watts

   $P = 0$ (rest)

   $R = M - H = (90 - 353)$ watts

   $R = -263$ watts   Minus value indicates decreasing thermal energy of body.

APPLICATIONS

A. Illustrative Problem Solving.

The problems in this section can be solved by selection of one or more of the following equations:

$$H_d = K_d A \left(\frac{\Delta T}{\Delta X}\right)$$
$$H_v = K_v A (T_1 - T_2)$$
$$H_R = (5.7 \times 10^{-8} \text{ watts/m}^2\text{-°K}^4)(eA)(T^4 - T_a^4)$$
$$H_E = (2400 \text{ joules/gram}) \frac{\Delta m}{\Delta t}$$

$$M - R = H_v + H_R + H_d + H_E + P \qquad \text{(D.3)}$$

The Table D.1 in this module is also to be considered as a resource. These problems are gradated in order of difficulty. The first require relatively simple manipulations while the latter demand more reasoning skills.

1. In an experiemnt on human subjects, a nude man is placed in a room with still air and room walls at 17°C. His initial skin temperature is 33°C. The air and wall temperature is then raised to 34°C and the skin temperature is measured at 35°C. If all the heat transfer from the body is attributed to radiation and convection, estimate the initial and final rates of thermal energy loss by each mechanism per sq. meter.

2. Use the information given in this module to complete the table below. Please add additional environmental conditions to the list suggested.

Environmental Conditions	Major heat loss mechanism	Other minor heat loss mechanisms
1. Resting human in cold room with cold walls and still air.		
2. Human doing light moderate exercise in large room with cool walls; small to light air movement.		
3. Lightly clothed human in "walk-in deep freeze compartment." Very cold air, light air movement, freezing wall temperature.		
4. Human with shorts cleaning hot attic on summer afternoon. Attic fan provides moderate air movement, wall and air temperature very high.		
5. Lightly clothed resting on a recently filled water-bed. Water temperature cold, air temperature and air velocity moderate with wall temperature cool.		

3. Consider a human subject ($A = 2m^2$) not moving relative to the air. The air and walls have an ambient temperature of 20°C. If this subject is resting (BMR/area = 50 watts/m^2), evaluate the approximate radiant, convective, and evaporative thermal energy loss rates.

4. Again considering the subject of the previous problem (3), evaluate what must be the skin temperature if the radiative rate is to be as calculated above. In doing this calculation, it is fair to assume that the (normal) subject is clothed, and the therefore the surface area available for heat flow is (A/4). Now using this skin temperature value, calculate what must be the coefficient of convection. Is this a reasonable value? Finally, evaluate the requisite rate of evaporative water loss under these conditions.

5. In order for the temperature regulative mechanisms of the body to operate effectively, they must respond quickly enough to temperature changes so that control can be exercised. To a first approximation, it is the heat capacity (better, "thermal energy capacity") of the body which fixes the response time of the internal temperature to a change in metabolic rate.

   If one assumes a subject as in problems (3) and (4) above, and takes m = 60 kg. as the subject's mass, then one can estimate the time it takes the entire body to rise 1°C in (internal) temperature in response to a doubling of metabolic rate by assuming that, again to a first approximation, no additional heat flow occurs than in the initial activity state. Since the body tissue is largely water, assume a body heat capacity for the body of

$$C_{body} = (1 \text{ cal/gm°C})(60 \text{ kg}) = 60 \times 10^3 \text{ cal/°C} = 2.4 \times 10^5 \text{ joules/°C}$$

Use these values to estimate the time for this body to rise 1°C in temperature if the metabolic rate goes from M = BMR = 100 watts to M = 1200 watts (running up a flight of stairs).

6. Again using the subject of problem (3), faced with the problem of having to dissipate a thermal energy at the rate of M = 500 watts (hard, steady exercise), what would have to be the skin temperature (calculated in the manner of problem (4)) to accomodate this higher heat flow rate. If this value turns out to be physically unreasonable, then you must state what can be done by the subject to accomodate this higher heat flow rate. You must, in every case, justify your recommendations with calculations and reasons.

7. Below is a chart of data listing what is frequently called the Wind-Chill Index. This provides, for a given actual temperature and wind speed, an "effective" temperature which is that which would produce the same total heat flow rate if the wind speed were zero. These data were obtained by the National Weather Service from measured cooling rates, at different temperature and wind speed conditions, of water within a plastic bag. (This means that evaporation was a negligible factor.)

   Develop a scheme of analysis which will allow you to obtain the convection coefficient as a function of velocity from these data. Make a graph of this relationship. Are you able to obtain a single relationship for all given temperatures or not? Comment on this.

ambient temperature \ wind speed (m/sec)	calm	2.5	5.0	7.5	10	12.5	15
-12	-12	-14	-23	-28	-32	-34	-36
-18	-18	-21	-29	-34	-39	-42	-44
-23	-23	-26	-36	-43	-47	-51	-53
-29	-29	-32	-43	-51	-56	-59	-61

WIND-CHILL INDEX OF EFFECTIVE TEMPERATURES

B. Applications for the Laboratory.

1. The object of this exercise is to examine the "thermal lag" time (or response time) of the simulated body (i.e., ball) to a change in its level of internal energy dissipation.

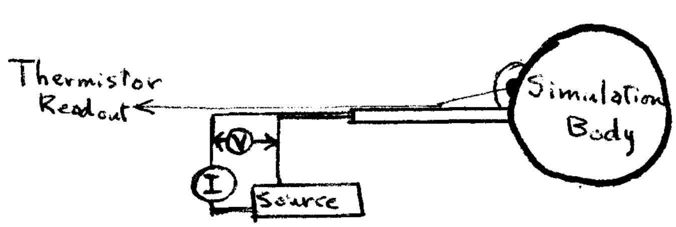
   Starting with the body at ambient temperature, switch on the input energy at some reasonable level. Record the temperature versus time relationship (and graph it) until a steady-state temperature is achieved.

   Again increment the input energy, and record the progress of the temperature versus time as it ascends to a new, higher steady-state value. Repeat once more.

   From these graphs, obtain values for the time required to achieve 1/2 of the total temperature jump in each case. Are these values nearly the same? These can be called the thermal response times of this system.

2. The object of this exercise is to establish the state of the simulator body (i.e., ball) as closely as possible to the normal physiological state of the human body.

   If the thermistor attached to the simulator body has not been calibrated so that the connection between its Celsius temperature and the thermistor current is known, then do so now using a water bath over the range 20° → 40° Celsius, and an ordinary laboratory glass/mercury thermometer as the comparison standard.



Arrange meters to simultaneously measure the input current (charge per unit time) I and the input current's voltage (energy per unit charge) V. Together, their product is the input power P = IV to the simulator body.

Now find the value of input power which achieves a steady-state operating temperature (of the ball) somewhere in the range 35° → 37°C. Call this the rest power. This temperature is, of course, in the proper physiological range for the human body interior.

Now using this rest power state, and its corresponding operating temperature, as a point of departure, measure the thermal response time by incrementing the power first up by a factor of two, and then later down by a factor of one-half. In each case, evaluate the response time as in exercise (1). Be careful to monitor the input power closely, as the shifting temperature of the heating coil within the ball will require varying combinations of I and V to achieve the constant, steady input power value required for these measurements.

3. The object of this exercise is to test the influence of different feedback lag times on the ability to regulate temperature.

   Using the rest power level for input power established in exercise (2) above, set the simulator body at its steady-state value corresponding to the physiologically normal value (35° → 37°).

   Increase the input power five-fold. Notice that this corresponds to a change in activity from rest to steady cycling at a 100 watt output power level in the case of the human body. Carefully and persistently monitor this power throughout now so that power changes are not a factor in temperature control.

Now with the input power held steady at this new high activity level, use the fan to attempt to control temperature at its original (35° → 37°) level. Record the temperature versus time each time the temperature is monitored to decide whether to adjust the air velocity. However, you must do this monitoring only at prescribed intervals. Do two cases:

(a) monitoring interval = 1/2 (thermal response time)

(b) monitoring interval = 2 (thermal response time)

In both cases, proceed until a reasonably steady state of control ensues. Thermal response time should be that value measured in exercise (2) above.

Now compare the temperature versus time graphs for cases (a) and (b), and describe any differences perceived in the effectiveness of the temperature regulation process between these two cases. What is the effect of feedback time?