Conductive Heat Exchanges at Terrestrial Surfaces as Influenced by Changing Air Density[1]

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Introduction

This study is limited to some considerations of heat exchanges by conduction between the free atmosphere and surfaces submerged in it.

There are many articles dealing with the effects of conduction with respect to plant and animal bodies. The literature on heating and ventilating is full of tables and text concerning heat exchange between objects and the surrounding air. There are, also, numerous expositions of so-called "comfort indexes" and the like: all worthy within themselves, but none of which seem to have covered the subject from the viewpoint of the effects of differing air density, i.e., changes in atmospheric density occurring with increasing altitude above sea level and the resulting effects on conductive heat exchanges at living and terrestrial surfaces submerged in this less dense atmosphere.

General physics texts, such as Semat (5), confine most of their discussion of conduction to what may be termed "closed" systems—systems in which the amount of available heat and the masses of the interacting materials are fixed throughout. While these models state the basic facts of conduction in mathematical form, these equations must be modified for application to conditions which exist in the out-of-doors. Specifically, they must be modified to encompass the action of conduction between the open environment and an object located at any point therein.

Fritz (2) gives a model for use of an atmospheric pressure ratio as a satisfactory replacement for computing a density ratio. This characteristic of the conductive process was recognized by Buettner (1), when he included a density factor as an essential part of his equation for conductive heat exchange between living organisms and the atmosphere. Application of these general physical principles of conduction to specific biological situations have been made possible by the previous writings of Waggoner (7), Buettner (1), Stacy et al. (6), Platt and Griffiths (4), and others. Adaptations have been made by the authors from facts gleaned from these writings.

Procedures

"Conduction" is defined as the exchange of heat between two distinct masses in contact with one another assuming that one is warmer than the other. In accordance with the kinetic theory of conduction such heat exchanges are the integral of energy exchanges of the molecules composing the two different masses in contact. In the atmosphere, air molecules surround objects located therein. Therefore, conductive heat exchanges are continuous so long as a temperature gradient exists.

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But the rate of exchange between solid masses surrounded by air depends on the conductive characteristics of that mass, plus the temperature gradient and the mass contact of air molecules over a given time. It follows that the conductive heat exchange will be affected by both motion (wind) and the mean density of the motion or air density.

At sea level and for a surface standing vertically at right angles to the wind direction, the relationships are as expressed in Equation 1 introduced by Waggoner (7) as modified from Buettner (1).

$$H = 1.2V^{1/2}(t_b - t_a) \text{ Kcal/m}^2\text{/hr.} \qquad \text{(Eq. 1)}$$

where—

H = amount of heat exchange from the warmer to the cooler body in kilocalories per square meter per hour.

1.2 = a constant. (Used when results in $\text{Kcal/m}^2\text{/hr.}$ are desired).

V = wind speed in centimeters per second.

t_b = temperature of the body in degrees Centigrade.

t_a = temperature of the ambient air in degrees Centigrade.

Equation 1 in its existing form does not account for the important factor of decreasing densities with increased elevations above sea level. At lower densities, and a given wind speed, fewer molecular contacts will be made at any given air-object intersurface within a given time period. Because it is these molecular contacts which are the agents of conduction, it follows that the conductive rate at higher elevations will be less than at sea level. From this line of reasoning, Equation 1 was changed by Miller (3) to the existing form of Equation 2.

$$H = - [0.002V^{1/2}(t_b - t_a)][p/p_o] \text{ cal/cm}^2\text{/min.} \qquad \text{(Eq. 2)}$$

where—

0.002 = is the constant for $\text{cal/cm}^2\text{/min.}$

p = is the measured barometric pressure at a given elevation.

p_o = is the normal sea level pressure.

Other symbols are the same as those mentioned in Equation 1. The proper mathematical derivation and the use of a pressure ratio in computing air density values is illustrated by Fritz (2).

As a final change, the right side of the equation has been made negative to insure that its solution will always carry the proper sign with respect to whether heat is being gained or lost by a given surface. That is, heat losses will show the negative sign, heat gains the positive sign with respect to a surface.

To aid in obtaining the proper numerator for the element "p/p_o", Figure 1 gives the percentages of average air density at various surface temperatures and at various heights above sea level (3). To use, merely take off the percentage applying to the elevation above sea level at which the study is taking place. These percentage values were derived from an adiabatic chart entitled, "Arowagram" published by the Air Transport Association of America, Meteorological Committee, Chart 17. They are, as stated, only averages. For more accurate results it would be best that a mercurial or aneroid barometer from which readings of "station" pressure, "p_o", can be taken be available at the site of the study.

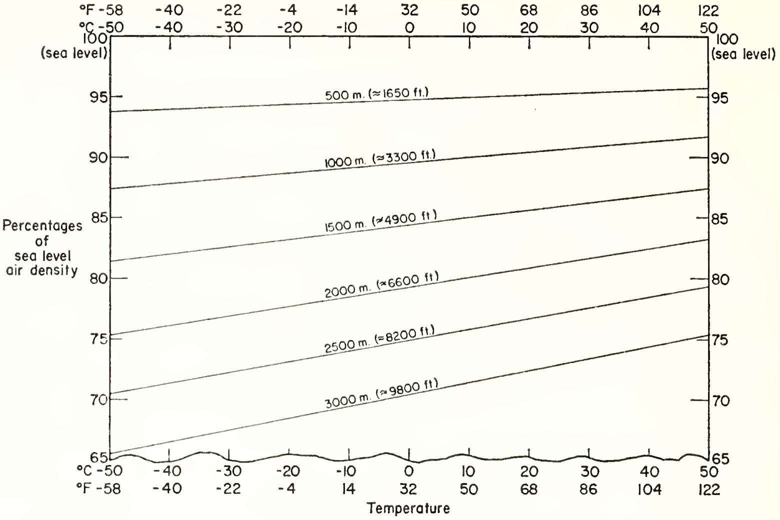

Figure 1. Average percentages of sea level air density at various altitudes.

If no wind measuring equipment is available, wind speeds can be estimated with reasonable accuracy by use of the Beaufort scale. To convert wind speeds to centimeters per second, multiply miles per hour by 45, or kilometers per hour by 28.

Results

The following results were obtained by solving Equation 2, assuming a vertical surface, densely shaded, standing at right angles to the direction of the wind flow and possessing a constant temperature of 40°C. Further, assuming the surface is insulated from conductive action on its leeward surface and all edges, the negative or positive conductivity with respect to a square centimeter of such a surface would be as follows:

A. Effects of changes in temperature differences:

Air temperature: —30°, 0°, 20°, 45° C.; wind, 5 mph; elevation, sea level.

Results: —2.10, —1.20, —0.60, and +0.15 cal/cm^2/min., respectively.

B. Effects of changes in wind speeds:

Wind speeds: calm, 5, 10, and 15 mph; air temperature, 0° C.; elevation, sea level.

Results: —0.16, —1.20, —1.73, and —2.08 cal/cm^2/min., respectively.

C. Effects of changes in elevation:

Elevation: sea level, 1000, 2000, and 3000 meters; wind, 5 mph; air temperature, 0° C.

Results: —1.20, —1.08, —0.95, and —0.85 cal/cm^2/min., respectively.

Further examples of results from Equation 2 are graphed in Figure 2 using 40° C. as the temperature of the surface at which the conduction is taking place. Graphs for any other sets of temperatures, wind speeds, and elevation data are similarly computed.

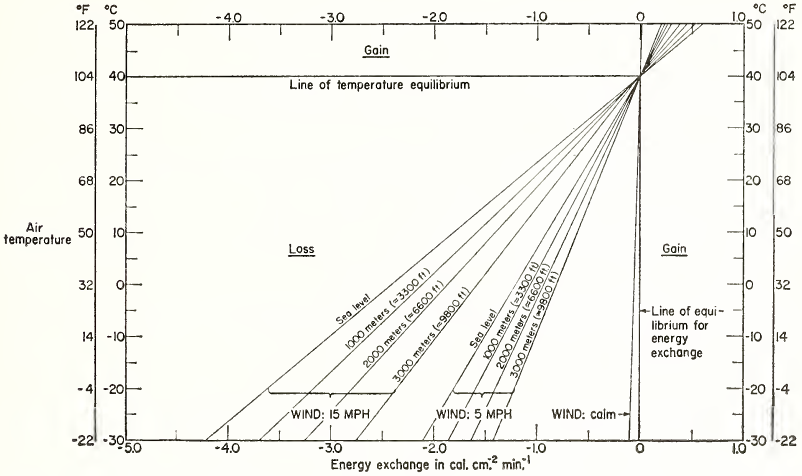

Figure 2. Examples of changes in conductive rates as functions of decreasing air density.

It is possible to make comparisons between any two or more sets of environmental conditions. For example, suppose that an animal, such as a dairy cow, is exposed at sea level and 1000 meters (about 3300 feet), the air temperature being 0° C. and the wind speed 12 mph. at both elevations. Assume that the cow's coat temperature under full insolation is 10° C. on a portion of the coat that is oriented normal to the wind on the windward side of the cow, then for this fraction of the body surface:

At sea level: $H = -[0.002(23.2)(10 - 0)][100/100] = -0.464$ cal/cm^2/min.

At 1000 meters: $H = -[0.002(23.2)(10 - 0)][89.6/100] = -0.417$ cal/cm^2/min.

Thus, under these prescribed conditions, the cow at sea level loses from this stipulated area of her coat 0.047 cal/cm^2/min. more by conductive heat exchange than she does at 1000 meters, solely because of the difference in atmospheric density.

Conclusions

Air density can make significant differences in conductive heat exchanges between the air and surfaces of differing temperatures submerged therein when the latter are subjected to changing elevations under certain environmental conditions.

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