ENTROPY BUDGETS OF DECIDUOUS PLANT LEAVES AND A THEOREM OF OSCILLATING ENTROPY PRODUCTION

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From an energy budget of a deciduous plant leaf in moderate conditions, entropy fluxes into or out of the leaf due to solar radiation, infrared radiation, evaporation of water and heat conduction are calculated. Net entropy flow into the leaf is negative. On the assumption that the entropy in the leaf is in a steady state, the entropy production in the typical deciduous leaf in moderate conditions (the solar energy absorbed by both sides of the leaf is $E_{\text{solar}} = 0.0602 \, \text{J cm}^{-2} \, \text{s}^{-1}$) becomes $S_{\text{prod}} = 1.8 \times 10^{-4} \, \text{J cm}^{-2} \, \text{s}^{-1} \, \text{K}^{-1}$. The positiveness of the entropy production shows that the Second Law of Thermodynamics certainly holds in the plant leaf. Entropy productions in other conditions are also calculated. The entropy production in the leaf $S_{\text{prod}}$ becomes a linear function of the solar energy absorbed by the leaf $E_{\text{solar}}$: $S_{\text{prod}} \approx (29.5 E_{\text{solar}}) \times 10^{-4}$. A theorem is presented: the entropy production in plant leaves oscillates during the period of one day, paralleling the daily solar energy absorbed by leaves.

1. Introduction. How entropy production changes with time in a living organism is an important problem in biological thermodynamics (e.g. Lamprecht and Zotin, 1978). Prigogine and Wiame (1946) have inferred that a living organism tends to a state of minimum entropy production; that is, entropy production in an organism decreases, reaches a minimum and remains afterwards at that level. Theoretical and experimental evidence of the validity of the Prigogine–Wiame theory was examined by Zotin and Zotina (1967) and by Zotin (1972) for development and growth of organisms. The recent results of entropy production calculations by Briedis and Seagrave (1984) for the developing chick embryo show an agreement with the Prigogine–Wiame theory. However, theoretically the theorem of minimum entropy production holds only for systems near to equilibrium (e.g. Nicolis and Prigogine, 1977); on the other hand, motions and reactions of substances occurring in organisms will be far from equilibrium. Hence, it is not always possible to claim that the theorem of minimum entropy production can be applied to all phases of processes in living organisms: the time-course of entropy production in some cases may differ from that of the Prigogine–Wiame theory.

In order to examine time-dependence of entropy production, it is necessary to obtain values of entropy production in organisms. In the present paper entropy flows and entropy productions in deciduous plant leaves, as examples of organisms, are calculated based on the energetics given by Nobel (1970) and
by Gates (1963) by use of the theoretical methods developed by Aoki (1987). Then, a theorem on entropy production in leaves is presented: entropy production in plant leaves does oscillate in steady state within the period of one day, paralleling the daily solar energy absorbed by leaves. This gives another theorem on entropy production in organisms; it is different from the Prigogine–Wiame theory.

For an understanding of the logical context of this paper, some fundamental knowledge on physics of radiation entropy is required, which is described, e.g. in Planck (1959), Landsberg (1961), Spanner (1964), Landsberg and Tonge (1979) and Aoki (1982, 1983, 1987).

2. Entropies Associated with Shortwave Solar Radiation. Consider a horizontal, flat and thin deciduous leaf exposed to full solar radiation at sea level where the energy flux of global (total) radiation is $E_i = 1.20 \text{ (cal cm}^{-2} \text{ min}^{-1}) = 0.0837 \text{ (J cm}^{-2} \text{ s}^{-1})$ [see the top line of Table 7.3 of Nobel (1970)]. We assume that the ratio of the energy of diffuse solar radiation to that of global radiation is $d = 0.20$. Also suppose that the reflectivity of solar radiation by the earth’s surface is $r = 0.20$ and that the absorptivity of the leaf to solar radiation is $\alpha = 0.60$ [Table 7.3 of Nobel (1970)].

Let us calculate solar radiation entropies absorbed by the leaf surface. We will follow a line of discussion described in Appendix of Aoki (1987). First, consider direct solar radiation. The energy of direct solar radiation incident per unit time on a unit area of the leaf surface is

$$E_{dr} = E_i \times (1 - d)$$

$$= 0.0670 \text{ (J cm}^{-2} \text{ s}^{-1}). \quad (1)$$

The corresponding solar entropy flux is given by [see equation (A10) of Aoki (1987)]

$$S_{dr} = 2.31 \times 10^{-4} \text{ (K}^{-1}) \times E_{dr}$$

$$= 0.155 \times 10^{-4} \text{ (J cm}^{-2} \text{ s}^{-1} \text{ K}^{-1}). \quad (2)$$

Next, the energy of diffuse (scattered) solar radiation incident on the leaf is

$$E_{sc} = E_i \times d$$

$$= 0.0167 \text{ (J cm}^{-2} \text{ s}^{-1}). \quad (3)$$

The specific intensity of diffuse solar radiation is given by [see equation (B2) of Aoki (1987)]

$$K_1 = \frac{E_{sc}}{\pi} = 5.33 \times 10^{-3} \text{ (J cm}^{-2} \text{ s}^{-1}). \quad (4)$$