$\boldsymbol{j}_e \nabla 1/T$), free energy ($\mu g$) generation, Joule effect ($\boldsymbol{j}_n \nabla \mu$) and expansion of the volume that contains the particles ($\nabla \boldsymbol{j}_\omega / T$). This equation is very important and will be used to prove the thermodynamic consistence of solar cells.

4.2.4 An Integral View

Fluxes, $\dot{X}$, of the thermodynamic currents, $\boldsymbol{j}_x$, will be frequently used in this paper. In this text, they will be also called *thermodynamic variable rates*. By definition, the following relationship exists:

$$\dot{X} \doteq \int_A \sum_i \boldsymbol{j}_x \, \mathrm{d}A \tag{4.14}$$

where the sum refers to the different subsystems with different velocities to be found at a given position. A is the surface through which the flux is calculated. Actually, $\boldsymbol{j}_x \, \mathrm{d}A$ represents the scalar product of the current density vector $\boldsymbol{j}_x$ and the oriented surface element $\mathrm{d}A$ (orientation is arbitrary and if a relevant volume exists the orientation selected leads to the definition of *escaping* or *entering* rates).

4.2.5 Thermodynamic Functions of Radiation

The number of photons in a given mode of radiation is given [9] by the well-known Bose–Einstein factor $f_{\mathrm{BE}} = \{\exp[(\varepsilon - \mu)/kT] - 1\}^{-1}$, which through equation (4.3) is related to the grand canonical potential $\Omega = kT \ln\{\exp[(\mu - \varepsilon)/kT] - 1\}$. In these equations, most of the symbols have been defined earlier: ε is the photon energy in the mode and k is the Boltzman constant. The corresponding thermodynamic current densities for these photons are

$$\boldsymbol{j}_n = f_{\mathrm{BE}}\mathbf{c}/(Un_r); \quad \boldsymbol{j}_e = \varepsilon \boldsymbol{j}_n f_{\mathrm{BE}}\mathbf{c}/(Un_r); \quad \boldsymbol{j}_\omega = \Omega \mathbf{c}/(Un_r) \tag{4.15}$$

where $\mathbf{c}$ is the light velocity (a vector since it includes its direction) in the vacuum and n_r is the index of refraction of the medium in which the photons propagate, which is assumed to be independent of the direction of propagation. Thus, $\mathbf{c}/n_r$ is the velocity of the photons in the medium.

The number of photon modes with energy between ε and $\varepsilon + \mathrm{d}\varepsilon$ is $8\pi U n_r^3 \varepsilon^2/(h^3 \mathbf{c}^2)\, \mathrm{d}\varepsilon$. When the modes with energies $\varepsilon_m < \varepsilon < \varepsilon_M$ are taken into account, the total grand canonical potential of the photons, Ω_{ph}, associated with these modes is the sum of the contributions from each mode and can be written as

$$\Omega_{\mathrm{ph}}(U, T, \mu) = \frac{8\pi U n_r^3}{h^3 \mathbf{c}^3} \int_{\varepsilon_m}^{\varepsilon_M} \varepsilon^2 kT \ln(1 - \mathrm{e}^{(\mu - \varepsilon)/kT})\, \mathrm{d}\varepsilon \tag{4.16}$$

where h is the Planck's constant.

Photons do not interact among themselves, such that temperatures and chemical potentials can be different for each mode. This means that they can be a function of the energy and of the direction of propagation. In the non-equilibrium case they can also be a