Annals of Physics 363 (2015) 457–475

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Friction in macroscopic thermodynamics: A kinetic point of view

João P.S. Bizarro

Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 24 November 2014
Accepted 6 October 2015
Available online 22 October 2015

Keywords:
Friction
Irreversible thermodynamics
Kinetic theory
H theorem
Brownian motion
Landauer's bound
Granular rotators
Current drive

ABSTRACT

To provide a solid support to a macroscopic framework developed to explicitly account for friction in thermodynamics, a kinetic description of frictional dissipation is developed. Using either a dissipative Fokker–Planck equation for Brownian motion or a Boltzmann equation with a friction-force term added, it is shown that both approaches lead to the emergence of the macroscopic thermodynamic relations that state the first and second laws with friction. The analysis is directly applied to the problem of determining the minimum amount of heating generated by memory erasure, known in computer science as Landauer's bound, and leads to a better understanding of the energetics behind the latter. A generalisation of Boltzmann's *H* theorem to include friction explicitly is also recovered, and the thermodynamics of granular rotators acted by a frictional torque and of radio-frequency (RF) current drive of fusion plasmas, in which collisional drag is present, are addressed as well. Various physics results are revisited employing the first and second laws with friction that have been derived from the appropriate dissipative kinetic equations, lower bounds for entropy production rates being derived both for granular rotators and for RF current drive.

1. Introduction

The incorporation of friction in thermodynamics has attracted interest since, at least, the introduction of sliding friction as a paradigm for irreversible quasistatic processes [1], has often been

E-mail address: bizarro@ipfn.tecnico.ulisboa.pt.

http://dx.doi.org/10.1016/j.aop.2015.10.007
0003-4916/

the concern of practitioners in finite-time thermodynamics [2–6], as well as of more fundamentally minded physicists and chemists [7–12], and has recently been the object of a more systematic effort whereby frictional dissipation has been included explicitly in first- and second-law analysis [13], which has lead to a framework that has already been applied to study the performance of thermal engines with friction [14]. Assuming an isothermal process and that friction-generated heating is fully dissipated in the surroundings,[1] or environment, the outcome of such an effort can be summarised as[2]

$$dU = đQ_{\text{exch}} + đW_0 - đW_{\text{fric}} \tag{1}$$

and

$$dS \geq \frac{đQ_{\text{exch}}}{T_0} - \frac{đW_{\text{fric}}}{T_0}, \tag{2}$$

(2) hereabove posing as an example of a refinement of the Clausius inequality [13]. Equations (1) and (2) read, respectively, as the first and second laws for a system whose internal energy changes by dU and entropy by dS when in thermal contact with the environment, which is at an absolute temperature T_0 and from which the system receives the amount of heat $đQ_{\text{exch}}$ and of work $đW_0 - đW_{\text{fric}}$, $đW_{\text{fric}}$ representing that part of the work $đW_0$ performed by the surroundings that is lost due to friction. Note that, because of frictional dissipation, the net amount of heating energy $đQ_0$ coming out of the surroundings is not simply equal to $đQ_{\text{exch}}$ but is here given instead by [13]

$$đQ_0 = đQ_{\text{exch}} - đW_{\text{fric}}. \tag{3}$$

Even if only out of a pedagogical concern, it is always instructive and useful to support a macroscopic framework with an underlying description at the atomic or molecular level [15],[3] whence this article, whose purpose is precisely to rederive (1) and (2) from well-known kinetic equations. These will be the Fokker–Planck and Boltzmann equations written with a frictional force term, the former appropriate for systems not very far from equilibrium, so they can be modelled by a Brownian type of motion, the latter suited for truly non-equilibrium situations [16,17]. Hence, in Sections 2 and 3, the macroscopic relations (1) and (2) will be shown to emerge by carrying out appropriate ensemble averages over dissipative forms of the Fokker–Planck and Boltzmann equations, respectively. Caring for the application of the framework here developed to actual physics problems, thus keeping an eye on the applied side of physics, the analysis will be used to address an important question originally raised in computer science, when trying to establish the limitations posed to computing performance by the fundamental laws of physics: the so-called Landauer's bound for heating generation due to memory erasure [19–22]. In addition, and for completeness, a recent generalisation of Boltzmann's H theorem to systems where frictional dissipation must be explicitly accounted for will also be recovered [23], the interest in deriving H theorems in kinetic theory accounting for non-conservative forces being not new [24]. Addressed as well, in Section 4 and using both a Fokker–Planck and a Boltzmann description, will be granular rotators, in which the effect of collisions with the particles of a granular gas can be counteracted by a frictional torque and a viscous drag, and where frictional dissipation plays an obviously crucial role [25–27], such devices falling under the classification of Brownian motors, or ratchets [28]. A further example still, dealt with in Section 5, will be the case of radio-frequency (RF) current drive of fusion plasmas, in which case the electron kinetics may be reasonably well described in the high-velocity limit by a one-dimensional Fokker–Planck equation [29–33]. Finally, the paper will come to its end in Section 6, where the analysis and results will be summarised and conclusions will be presented.

[1] More specifically, put $\alpha = 0$ in [13] and set also $T = T_0$ therein.

[2] With α nil, (1) can be obtained by combining Eqs. (1), (13) and (20) given in the first of references [13], whereas (2) stems directly from Eq. (45) in the second.

[3] One has been tempted to call such a description microscopic but has been cautioned against it with the argument that the canonical understanding of the latter is that the dynamics must be time-reversible Hamiltonian dynamics, which is obviously not the case with either the Fokker–Planck or Boltzmann equations, both of which, even if initially structured around Liouville's equation, derived from Hamilton's equations of motion, sooner or later in their derivation involve some closure or coarse graining that destroys time reversibility [16–18].