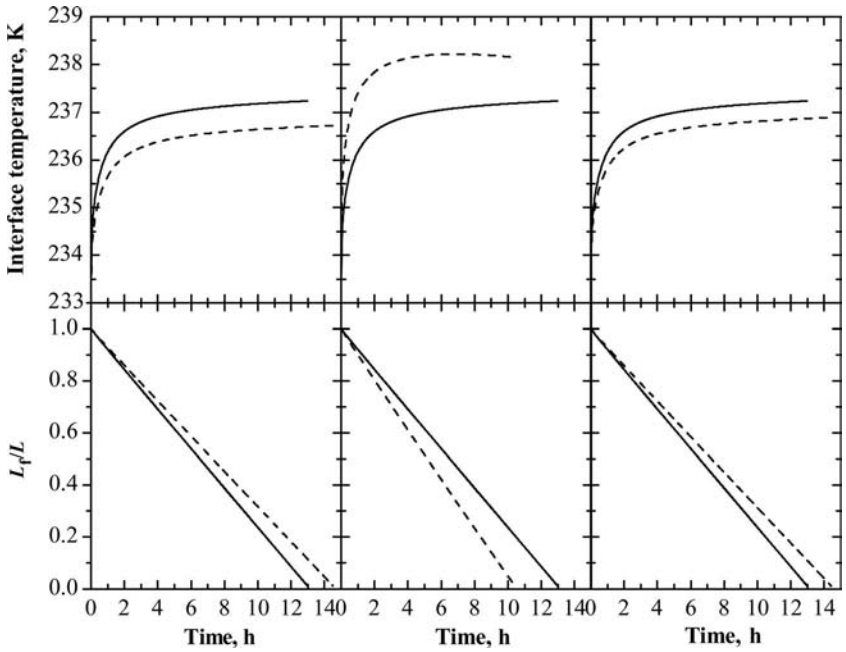

FIGURE 1 Comparison between the time evolution of the temperature (*upper graphs*) and of the frozen layer thickness (*lower graphs*) in a freeze-drying cycle of a 10% wt/wt sucrose solution (operating pressure = 10 Pa, $d_v = 14{\cdot}10^{-3}$ m, $L = 7.2 \times 10^{-3}$ m). Left-hand graphs: Dynamics in a vial placed over a shelf with $T_{shelf} = -15°C$ (*dashed line*) and in a vial placed over a shelf with $T_{shelf} = -12°C$ (*solid line*). The vials are considered perfectly shielded from radiation. Central graphs: Dynamics in a vial perfectly shielded for radiation (*solid line*) and in a vial at the border of the shelf, where radiation is relevant (*dashed line*). $T_{shelf} = -15°C$. Right-hand graphs: Dynamics in a vial placed at the border of the shelf, but shielded from radiation, (*solid line*) and in a vial placed in the central part of the shelf (*dashed line*), where pressure is higher. $T_{shelf} = -15°C$.

from the freeze-drying chamber (which is the most common case in industrial apparatuses), the size of the duct and of the isolating valve.

Since the experimental investigation of these issues is costly and time consuming, it is very interesting to explore them by using a computational approach, capable of giving meaningful predictions yet significantly reducing the extent of the experimental campaign. Such an approach is represented by CFD that, through a finite-volume numerical scheme (17), solves the continuity and Navier–Stokes equations along with other relevant governing equations (e.g., enthalpy balance) not only delivering reliable predictions, which can replace long and expensive experiments, but also providing engineers and scientists involved in equipment design with precious and very detailed insights. The main limitation of this technique stands in its description of the sublimating gas as a continuum (18), being therefore valid only when the Knudsen number (Kn) is smaller than 0.01. Although at the low pressures typical of freeze-drying operations the characteristic mean free path of the involved gas molecules can be quite large, under usual operating conditions (both for chamber and condenser) and for the most common industrial geometries this condition is almost always satisfied. Nevertheless, in the