Introduction: The first steam engines were built to raise water against gravity. The Martian seasonal frost cycle entails the evaporative removal of some 3x10^{16} kg of material from the northern lowlands, its transport as gas through the atmosphere, and its deposition as snow or frost some 5 km higher up in the south, and vice-versa: a cycle entailing considerable mechanical potential energy. While thermodynamic models have been applied to Martian dust devils, the concept of a heat engine has not been quantitatively applied to the Martian seasonal cycle. I discuss the energetics and entropy budget of this process.

Frost Cycle: The frost cycle on Mars has been observed from Earth for centuries. Orbital measurements (e.g. MGS laser altimeter data [1]) show that about 1 m of material is deposited polewards of about 60°, corresponding to ~3x10^{15} kg of snow. The cycle is not quite symmetric, for two reasons. First the orbital eccentricity makes southern summer hotter but shorter in duration. Second, the northern summer entails deposition of heat at a lower altitude, and thus a higher pressure. The thermodynamic implications of this have not received much attention in the literature.

Energetics: Whatever the climatic details of albedo effects, partitioning into sensible heat, radiative to space etc., the net effect of the seasonal cycle is to evaporate the material. With a latent heat of ~575 kJ/kg, this amounts to 1.7x10^{11} J, or about 10 MJ/m^2 of heat (per cap sublimation) averaged over the area of the planet. For the northern summer, the uphill transport of CO_2 yields 400 kJ/m^2, or a thermodynamic efficiency of 4% (this assumes the material is deposited on the surface as frost — if the material condenses at higher altitudes, more potential energy is generated, but is lost as frictional dissipation as the snowflakes descend.) Averaged over the surface of Mars, the mechanical work generated (and dissipated) by this transport is ~6 mW/m^2.

Engine Efficiency: The 5 km difference in elevation between northern lowlands and the south (ignoring the very localized topography of the permanent caps) leads to a pressure difference of about 50%, or in engine terms, a compression ratio (CR) of 2. The ideal thermodynamic efficiency of an engine is 1-(1/CR)^1, with γ the ratio of specific heats (1.28 for CO_2). Thus the ideal efficiency is ~18%.

Comparison with Earth’s Hydrological Cycle: Water substance is evaporated at the surface and forms clouds and precipitation. To a first order 1000 kg (1 m) of water is evaporated per m^2 per yr and is raised a few km before condensing; if 3 km is adopted the dissipation corresponds to 3x10^{11} J/m^2 or ~1 W/m^2 (though [2] gives ~2). This may be compared with the latent heat involved ~2x10^{11} J/m^2/yr to give a thermodynamic efficiency of only ~1.5%. Why so low? A factor may be the fact that the condensable is a minor constituent, so that its dilution after evaporation generates entropy by mixing [3] — this process may be factor on Mars as well, since Argon and Nitrogen can build up locally as the frost caps form (e.g. [4]).

Comparison with Frictional Dissipation: The mechanical work dissipated by surface friction is ~1/2pC_V V^3, where for Mars p=0.02 kg/m^3, and we assume a typical drag coefficient C_D=0.003. Note that a mean windspeed should not be used uncritically as the result depends on the cube of windspeed (i.e. the dissipation may be dominated by the high speed tail of the wind probability distribution [5]) — the Viking windspeed statistics [6], we suggest <V^3>^{1/3} ~10 m/s. As a result the frictional dissipation is ~0.03 W/m^2.

On Earth, the corresponding quantity is of order ~2 W/m^2 [7,8,9] Thus on Earth, the vertical transport of condensable material causes mechanical dissipation comparable with friction at the surface, but on Mars the condensable cycle is only about 2% as important.

Conclusions: The thermodynamic efficiency of the polar cycle is comparable with, and perhaps larger than, that of precipitation on Earth. Perhaps because the condensable does not intercept the abundant sunlight at low latitudes, however, the Mars frost cycle generates with a smaller proportion of the total dissipation in the climate system than water does on Earth.


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