Terraforming the Aral Sea Basin

Geomorphological and Anthropogenic Foundations (second part)

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II PART: THE POST-SOVIET ARAL SEA

During the second half of the twenty century, the vanishing of the Aral Sea was an ongoing reality. The primitivism of the irrigation system had the signature of an imminent catastrophe. In 2003-2004, Rob Ferguson just observed that "the Karakum canal was still sucking up a quarter of the Amu Darya's water"[3]. The old soviet irrigation scheme was incredibly inefficient and never underwent an updating.

The results of the Soviet insanity are well known. Figure 1 shows the appearance of the Aral Sea in 2002, already in phase of intense dryness. Lastly, Figure 2 shows an agonizing scenario from that once prosperous region.

But the post-Soviet Aral Sea, or what is left of it, now exists in a completely different technological context, which includes advanced scientific theories and techniques to be employed for good, as well as for evil, unfortunately. The expanded civil engineering for geoengineering, allied to others such as materials engineering, thermal systems engineering, and control engineering now enable us to make modifications on natural landscapes that were once impossible.

In view of the above discussed, the endorheic nature of the Aral basin seems to present a history of natural and anthropogenic transformations compatible with a proposal of regeneration via geoengineering. The main

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Fig. 1. Aral Sea in 2002 (source: NASA Gateway to Astronaut Photography)..

geoengineering proposal was presented by Badescu and Cathcart [1], the most plausible among those that have been discussed since the middle of the last century. This proposal, roughly speaking, based on the construction of pipelines between the Caspian Sea and the Aral Sea, was supplemented with concepts related to the idea of terraforming the Earth itself, developed in my recent work on the Aral Sea basin [13]. At this point, I would like to discuss theoretical aspects of control engineering and thermal systems engineering, trying to contribute to a partial recovery plan for the Aral Sea environment.

1 thermodynamical device for observation and control of the anthropogenic Aral Sea

An appreciation of the present conditions of the Aral, or rather Aralkum desert, allows us to say that the partial recovery of the old lake goes against an important conjuncture of irreversible processes, since critical morphological changes and progressive salinization have led to a profound and hardly reversible alteration of the biological system of the sea [6]. In addition to

Fig. 2. The last view of the eastern Aral in 2012. (source: NASA Gateway to Astronaut Photography)..

the massive environmental depreciation that occurred in the last 80-100 years, it must be taken into account that the endorheic condition of the Aral and its intense exposure to evaporation constitute a fragile ecosystem to be necessarily monitored under any recovery circumstances. Although it is possible to use simple control devices such as monitoring of water levels, control of salinity and water quality against pollutants, the issue becomes more complex due to the climatic extremes of the region and the albedo related to the vegetal cover of the cotton plantations. From a thermodynamic point of view, the observation of the entropy rates in our anthropogenic Aral Sea, at least theoretically, would be a useful scientific instrument for understanding the geophysical dynamics of this lake, having in mind some relation involving volume, pressure, entropy and temperature. The key to this observation may lie in the implementation of a closed cycle OTEC (Ocean Thermal Energy Conversion) device only for measurements from the differences between the temperature at the sea surface and the temperature in the depths (for a better understanding of the general principles of thermodynamics, please see the references [7], [10] and [12]).

As we know, OTEC devices generate electricity indirectly from solar energy by establishing a thermodynamic cycle, since an expressive portion of the solar radiation is retained by the surface layers of the seas. The surface heating and the gradual cooling of the water towards the bottom create a kind of thermal potential difference between the surface and the the lower levels. Thus, it is possible to establish a level of environmental equilibrium of the lake as a function of the net power generated by the turbine put into operation by the expansion of the ammonia vaporized by the thermal transfer from the sea water heated by the sun. Of course, this is not about producing electricity for consumption but, rather, an electrical marker of entropy monitoring. Nevertheless, Micklin reported ancient measurements of temperatures related to a significant thermocline in the deep Western Basin of the Large Sea, ranging from summer surface temperatures around 24°C to deep temperatures of 2°C - 6°C below 30 meters. Such temperatures would be sufficient in a new partial Aral even for the establishment of experimental stations for electricity generation or for desalination tests [9].

The decrease in water volume in the Aral Sea is closely linked to the following factors:

1. intense evaporation;
2. massive water losses of tributary rivers due to unsustainable irrigation techniques;
3. climate change caused by greenhouse gases.

The OTEC measuring device translates the difference in volume in terms of the reduction of the thermal potential difference, which consequently produces less power from the generating turbine.

1.1 Theoretical approach on the thermodynamics of the OTEC engine

In a recent work [12], I have deduced a thermodynamic equation especially designed for situations in which vigilance over system degradation, that is, the change in the volume of matter with respect to entropy variation, is a priority. I will make an explanation adapted to the present context, starting from the very reasonable hypothesis that our OTEC of measurement is able to mirror in a small scale what happens in the external environment. Although OTEC devices implemented under the Carnot cycle are unfeasible, by theoretical circumstances the intrinsic absolute efficiency of Rankine cycle and Carnot cycle compared are approximately equal. Also, however OTEC engines are well described by Rankine cycles, the efficience bound of any thermal engine is ever defined by the theoretical Carnot cycle. Lastly, it is good to stress that OTEC technology is still a subject of many studies before it becomes truly viable in large scale; our device is only a kind of sensor for entropic analysis, not intended to the production of usable electrical energy.

The description of heat exchanges via entropy variation presented below is valid for any thermodynamic system. In thermal systems engineering, it is clear that heat exchanges are closely related to four main variables: S (entropy), V (volume), T (temperature) and $\mathscr{P}$ (pressure). From the entropy equation we can write

$$TdS = dQ; \tag{1}$$

$$TdS = dE + \mathscr{P}dV. \tag{2}$$

If we establish the differential relation between the thermal energy and the couple $(\mathscr{P}, S)$ we do

$$\frac{\partial E}{\partial \mathscr{P}} = T\frac{\partial S}{\partial \mathscr{P}} - \mathscr{P}\frac{\partial V}{\partial \mathscr{P}}; \tag{3}$$

$$\frac{\partial E}{\partial S} = T\frac{\partial S}{\partial S} - \mathscr{P}\frac{\partial V}{\partial S}. \tag{4}$$

Again differentiating these expressions,

$$\frac{\partial^2 E}{\partial \mathscr{P}\partial S} = \frac{\partial T}{\partial S}\frac{\partial S}{\partial \mathscr{P}} + T\frac{\partial^2 S}{\partial \mathscr{P}\partial S} - \frac{\partial \mathscr{P}}{\partial S}\frac{\partial V}{\partial \mathscr{P}} - \mathscr{P}\frac{\partial^2 V}{\partial \mathscr{P}\partial S}; \tag{5}$$

$$\frac{\partial^2 E}{\partial S\partial \mathscr{P}} = \frac{\partial T}{\partial \mathscr{P}}\frac{\partial S}{\partial S} + T\frac{\partial^2 S}{\partial S\partial \mathscr{P}} - \frac{\partial \mathscr{P}}{\partial \mathscr{P}}\frac{\partial V}{\partial S} - \mathscr{P}\frac{\partial^2 V}{\partial S\partial \mathscr{P}}. \tag{6}$$

Since the order of differentiation does not matter, we have

$$\frac{\partial T}{\partial S}\frac{\partial S}{\partial \mathscr{P}} - \frac{\partial \mathscr{P}}{\partial S}\frac{\partial V}{\partial \mathscr{P}} = \frac{\partial T}{\partial \mathscr{P}} - \frac{\partial V}{\partial S}. \tag{7}$$

Assuming that $\mathscr{P}$ and S are jointly parametrized, that is,

$$\left(\frac{\partial S}{\partial \mathscr{P}}\right)_S = \left(\frac{\partial \mathscr{P}}{\partial S}\right)_{\mathscr{P}} = 0,$$

$$\frac{\partial V}{\partial S} = \frac{\partial T}{\partial \mathscr{P}}, \tag{8}$$

which is one of Maxwell's thermodynamic equations. Similar results are obtained by exchanging pairs of quantities to obtain the remaining equations. The equation (8) establishes a linking key for the control of the variation of the entropy, since it associates the variations of pressure, temperature and volume.

My research on the intrinsic relation between the variables S, $\mathcal{P}$, T and V led me to write a general equation of the second order, namely

$$\tilde{c}\frac{\partial^2 V}{\partial \mathcal{P} \partial S} = -\frac{1}{\mathcal{P}}\frac{\partial T}{\partial \mathcal{P}}, \tag{9}$$

with $\tilde{c}$ constant. By replacing equation (8),

$$\tilde{c}\frac{\partial^2 V}{\partial \mathcal{P} \partial S} = -\frac{1}{\mathcal{P}}\frac{\partial V}{\partial S}. \tag{10}$$

Since the order of differentiation does not matter,

$$\tilde{c}\frac{\partial}{\partial S}\left(\frac{\partial V}{\partial \mathcal{P}}\right) = -\frac{1}{\mathcal{P}}\frac{\partial V}{\partial S}. \tag{11}$$

The obtaining of primitives on both sides by anti-differentials, with $\mathcal{P}$ parametrized $((\partial \mathcal{P}/\partial S)_{\mathcal{P}} = 0)$, leads to

$$\tilde{c}\frac{\partial V}{\partial \mathcal{P}} = -\frac{V}{\mathcal{P}}. \tag{12}$$

This equation (It is obvious that for $\tilde{c} = 1$, we fall back into the situation of a perfect gas) can be organized in the form

$$\tilde{c}\frac{\partial V}{V} = -\frac{\partial \mathcal{P}}{\mathcal{P}}, \tag{13}$$

whose integration provides

$$\tilde{c}\ln\frac{V_2}{V_1} = \ln\frac{\mathcal{P}_1}{\mathcal{P}_2}. \tag{14}$$

From this we obtain

$$\left(\frac{V_2}{V_1}\right)^{\tilde{c}} = \frac{\mathcal{P}_1}{\mathcal{P}_2}. \tag{15}$$

This expression holds for polytropic processes [12]. Depending on the value of $\tilde{c}$, the process can be isobaric, isochoric, isothermal or isentropic. For the isentropic case, provided that $\tilde{c}$ is constant, it follows that

$$\mathcal{P}V^{\tilde{c}} = const., \tag{16}$$

known as the Poisson adiabatic equation, with $\tilde{c}$ being called the isentropic coefficient.

Although the equation (9) has been presented as an axiom, it follows from the application of the state equation of Grüneisen (as we know, although not much in the literature, the Grüneisen parameter has both a microscopic and a macroscopic definition, the first, referring to the vibrational frequencies of atoms in a given material, and the latter, referring to the thermodynamic properties such as thermal capacity and thermal expansion) [7] in the energy conservation equation (2), so that we have partials

$$T\partial S = \partial E + \tilde{c}(\frac{E}{V})\partial V. \tag{17}$$

Then we call P the fraction E/V, whence

$$T\partial S = \partial E + \tilde{c}P\partial V. \tag{18}$$

Dividing all terms by ∂P, we have

$$\frac{\partial E}{\partial P} = T\frac{\partial S}{\partial P} - \tilde{c}P\frac{\partial V}{\partial P}. \tag{19}$$

Given that

$$\frac{\partial E}{\partial S} = T, \tag{20}$$

it follows

$$\frac{\partial}{\partial P}\left(\frac{\partial E}{\partial S}\right) - \frac{\partial T}{\partial P} = 0; \tag{21}$$

$$\frac{\partial}{\partial S}\left(T\frac{\partial S}{\partial P} - \tilde{c}P\frac{\partial V}{\partial P}\right) - \frac{\partial T}{\partial P} = 0; \tag{22}$$

$$\frac{\partial T}{\partial S}\frac{\partial S}{\partial P} + T\frac{\partial^2 S}{\partial S\partial P} - \tilde{c}\frac{\partial P}{\partial S}\frac{\partial V}{\partial P} - \tilde{c}P\frac{\partial^2 V}{\partial S\partial P} - \frac{\partial T}{\partial P} = 0. \tag{23}$$

With the parameterization of P with respect to S,

$$\tilde{c}\frac{\partial^2 V}{\partial S\partial P} = -\frac{1}{P}\frac{\partial T}{\partial P}. \tag{24}$$

Now, if the Aral level varies significantly - and therefore its volume - this shall have a direct reflection on the temperature gradient (there shall be less temperature variation between the surface layers and the reference ground). According Carnot's principle, the maximum theoretical energy conversion efficiency of a cyclic heat tranfer engine varies with the difference between the temperatures at which the heat transfer occurs. Equation (24) shows the internal dynamics of cyclic heat transfer devices as the OTEC engine in focus (this kind of thermodynamic engine was detailed in references ([2], [8]), in this case considering the volume of an adjustable proportion mixture of amonia to be vaporized and expanded by thermal input from warm sea water, in a continuous loop, where the saturated vapor do work through the turbine before being condensed by the cold sea water. It is important to note that closed-cycle OTEC power systems operate at high pressures, and that irreversibilities occur in heat exchangers when thermal energy is transferred over a large temperature difference. Such irreversibilities mirror entropy change rates. The parameter $\tilde{c} > 0$ is in the last analysis the adiabatic coefficient of the adiabatic relation (16). It also corresponds to the polytropic index n, when it's the case. Since a typical Carnot machine operates under an efficience evaluated as

$$\eta_t = 1 - \frac{T_{II}}{T_I}, \tag{25}$$

where T_I is the input temperature and $T_I I$ is the output temperature, this clearly leads us to write that, for the OTEC heat engine in question, the efficiency could not exceed the maximum value, that is

$$\eta_t \leq 1 - \frac{T_{\mathrm{II}}}{T_{\mathrm{I}}}. \tag{26}$$

For a reversible cycle process we can have $\Delta S_{global} = 0$, otherwise $\Delta S_{global} > 0$. The logical way to establish an asymptotic relation between the heat engine efficiency and the Carnot machine efficiency is to introduce the irreversible coefficient φ, due to the irreversible events during human processes. So expression (26) can be rewritten as

$$\eta_t \leq \frac{1}{\varphi}\left(1 - \frac{T_{\mathrm{II}}}{T_{\mathrm{I}}}\right). \tag{27}$$

While most of the actual processes (natural and human) in the Aral basin are irreversible, φ can only asymptotically approach unit with the minimization of irreversible events. Thereby, the more φ is closer to 1, the less is the number of irreversible processes and the entropy variation ΔS. In other words, the number of configuration states of the system is just reduced as the processes assume only the states organized by the temperature gradient. Lastly, an example of processes that increase the rate of variation of environmental entropy is the wind transport of salts from the exposed sea bed, which has drastically reduced agricultural productivity.

1.2 The interaction of the OTEC engine with the environment

Whereas the entropy of a dynamical system always tends to grow in the direction of time, it is reasonable to assume that control actions only decelerate the advancement of entropy. Thus, it is appropriate to talk about the variation of entropy. Looking at presented engine, the total variation in the generation of entropy may be written as

$$\delta S_{tot} = \delta S_{int} + \delta S_{ext} \tag{28}$$

However, in my opinion, if what matters is the rates of change of the entropy, and if the entropy has the same direction as the arrow of time, then it is convenient to establish a Lagrange function as

$$\mathfrak{L} = \delta Q_{int}\dot{f}(H) + f(H)\frac{\delta Q_{ext}}{\tau_{ref}}, \tag{29}$$

where $f(H)$ is a generalized coordinate given by the Heaviside function of time interval

$$f(H) = (\tau - \tau_0)H(\tau - \tau_0), \dot{f}(H) = H(\tau - \tau_0).$$

In Macaulay kets, this Lagrangian form assumes

$$\mathfrak{L} = \delta Q_{int}\langle \tau - \tau_0 \rangle^0 + \langle \tau - \tau_0 \rangle^1 \frac{\delta Q_{ext}}{\tau_{ref}}. \tag{30}$$

I have called this Lagrangian "ergodetic", meaning that it refers to the thermal energy evolving along short intervals. The second term refers to the effects of the external supply of thermal energy concentrated in a given time interval over a reference period. For $\tau < \tau_0$, the Lagrangian vanishes according to kets rules. In other words, there is no thermal energy going through the past, which is the same thing to say that entropy ever points to the future. Now, let us take Euler-Lagrange differential equation for a non-dissipative situation,

$$\frac{d}{d\tau}\left(\frac{\partial \mathfrak{L}}{\partial \dot{f}(H)}\right) - \frac{\partial \mathfrak{L}}{\partial f(H)} = 0. \tag{31}$$

This implies that

$$\frac{d}{d\tau}(\delta Q_{int}) - \frac{\delta Q_{ext}}{\tau_{ref}} = 0 \therefore \tag{32}$$

$$\boxed{\delta \dot{Q}_{int} = \frac{\delta Q_{ext}}{\tau_{ref}}}. \tag{33}$$

A symmetry of this type must be pursued and serves as an equilibrium model to be imitated by control devices, establishing real links between equipments and external environment. The introduction of the H function as generalized coordinate aims to establish small time intervals along which the variation of entropy appears as an evolutionary signature, since $\delta Q = T\delta S$; moreover, to null the Lagrangian from any instant to the past. Thus, entropy seen as a quantity associated with the energy failure of the system, must be tied, by its very definition, to the time arrow, never pointed to a time before the instant of observation. In its one-way temporal bond with energy, it is a trace of system's evolution. Therefore, the proposed physical ergodetic Lagrangean avoids any mathematical abstractionism that seeks to symmetrize the concept of entropy.

Finally, all the theory presented above needs to be considered in the control algorithms to operate the OTEC station.

2 Conclusion

In view of the succinct history of the transformations in the Aral Sea basin during the last centuries, with the appearance and disappearance of canals, destructions and reconstructions of ancient empires, one can conclude that, with all the available technology in the 21st century, it is possible to induce a partial restoration of the old Aral, being exclusively a question of State policies. The water retention experience in Northern Aral is a modest example of how simple engineering can yield acceptable results. Water disputes in Central Asia certainly need to be settled by mutual agreement between the countries that depend on the region's major rivers, a necessary understanding that will need to be repeated many times in different parts of the globe if mankind has plans to stay here any longer time than it seems we will indeed.

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To Nice Chaves Costa
in memoriam.

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