



Entransy concept and controversies: A critical perspective within elusive thermal landscape



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ABSTRACT

The concept of 'entransy', a product of heat and temperature, originally called 'heat transport potential capacity', was introduced in 2003, as analogy to product of electrical charge and voltage, as well as other similar quantities. The concept has been extended to entransy property, as integral product of 'stored heat' and temperature, $MC_v T^2/2$, thus representing quantity and quality of stored heat, or thermal energy in isochoric processes without work interactions. The entransy has been used for analysis and optimization of many heat transfer processes as described in many publications since its introduction, and is under further development. Later, the entransy concept has been criticized and denounced by a group of researchers, thus creating controversies that need to be put in a broader, historical and contemporary perspective, which is the main goal of this paper. Despite the need for further clarifications and development of the new concept, it would be premature and unjust to discredit entransy, based on limited and subjective claims, as if the 'already established' concepts and methodologies are perfect, and do not need alternatives and innovations, as if further progress is not needed.

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1. Introduction

The *entransy concept* [1,2], while still in development [3] (with 173 references) and with certain deficiencies, has been challenged and criticized by several publications [4–9], as “inconsistent and not needed ... having lack of content in physics ... redundant to entropy,” among others, thus creating controversies, as argued in published rebuttals by the Entransy Authors [10–14]. The ‘entransy concept and controversy’ need to be put in broader, including historical and contemporary perspective, with regards to still-elusive nature and many open issues within thermal phenomena. It appears that some criticism without due rigor of objective and all-inclusive analysis, of all positives and negatives of a newly developing concept, is not justified.

This author is familiar with and in occasional contacts with Professor Guo's group which introduced the ‘entransy’ concept, as well as with Professor Bejan, whose followers have criticized the new concept, thus generating an ‘Entransy Controversy’ [14]. Furthermore, this author is devoted to further comprehension of the fundamental *Laws of Thermodynamics* and nature, from *caloric* theory to *Carnot's* reflections, to Clausius theory of heat and entropy, to the contemporary ‘extension’ of entropy and challenges of the

Second Law of thermodynamics [15–19]. In that regard, after long contemplation, a critical perspective of entransy concept and the following controversies within elusive ‘thermal landscape’, is first time presented and discussed here by this author.

Regardless of entransy redundancy, being derived from other physical quantities, as are the enthalpy, free energy and exergy, for example, it does not diminish entransy uniqueness and usefulness in thermal analysis and optimization. Actually, it is contended here that the entransy, due to its unique nature, may contribute to better comprehension of often obscured thermal phenomena. Despite the need for further development and clarifications of the new concept, it would be premature and unjust to discredit entransy, based on limited and subjective claims, as if the “already established” concepts and methodologies are perfect, and do not need alternatives and innovations, as if further progress is not needed.

2. Heat and elusive thermal energy

Nature of heat was a mystery for a long time and still is elusive. Lavoisier proposed that “*heat is a subtle, weightless substance called caloric.*” Being a substance, the conservation of caloric was a central assumption, long before the energy conservation was established. Regardless of ingenious developments, the ‘caloric theory’ has been discredited since the ‘caloric’ was not obviously conserved during dissipative ‘heat generation’ processes, like drilling, and similar,

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nor in heat engines, as mistakenly assumed by Sadi Carnot [16]. To the contrary, after Einstein discovered ‘generation’ of energy from mass, $E = Mc^2$, the First Law of energy conservation was not discredited, but have been augmented with Einstein’s theory. In fact, nothing is wrong with the caloric theory, it is invaluable in modern calorimetric property measurements, it only should be objectively re-assessed and augmented with modern thermal developments.

Heat is a unique and universal concept representing energy transfer of thermal random-motion and its interactions, all other energy transfers classified as different types of work. The stored heat or ‘thermal energy’ represents stored energy of relevant thermal motion and interactions due to thermal heat transfer or dissipation-conversion of all other energy types to thermal heat. The term ‘thermal heat’ is used here to represent holistic meaning of both, the stored thermal energy, and heat as transfer of the stored thermal energy.

There is an important peculiarity about spontaneous heat transfer processes without any work interactions (like within heat exchangers): no heat conversion to work like in heat engine, and no other heat generation from work dissipation, but only the Carnot’s ‘thermal work-potential dissipation’ to heat itself – resulting in conservation of heat, i.e., conservation of thermal energy [15–17,19]. Like original caloric, the thermal energy is conserved on its own, but spontaneously degraded to lower temperature, since it cannot be spontaneously reversed back to higher temperature. We like to name such processes, without work interactions, as ‘caloric processes’ or ‘caloric heat transfer’, also called ‘pure heating or cooling’ by Guo’s group, referred here as Entransy authors. We also could define ‘reversible heat transfer,’ when the heat source and sink are at a finite temperature difference, achieved by an ideal Carnot cycle so that thermal work potential is extracted (instead of being dissipated into heat, like in the above caloric processes), while reducing temperature level so that heat transfer takes place at infinitesimally small temperature difference at each temperature level ($dT \rightarrow 0$) [15,17,19], see Fig. 1.

Starting from Clausius till nowadays, the obvious but in general not quantified thermal energy, is ‘lumped’ into the internal energy,

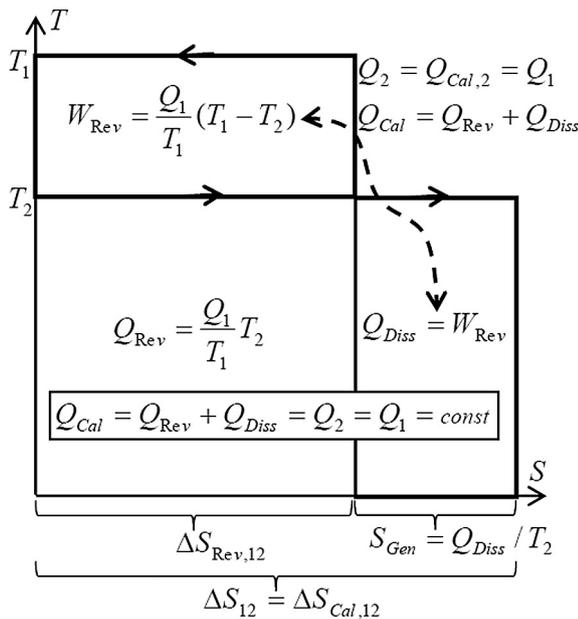


Fig. 1. During a caloric heat transfer process between two thermal reservoirs, the work potential, W_{Rev} , is completely dissipated into heat at a lower temperature, Q_{Diss} , which after being added to the reduced reversible heat at lower temperature, Q_{Rev} , will result in conserved heat or thermal energy, $Q_{Cal} = Q_{Rev} + Q_{Diss} = constant$, with increased, generated entropy in the amount of dissipated work potential per relevant absolute temperature [17].

the latter well-quantified and tabulated in Thermodynamic reference books. Some (or many) argue that thermal energy is not definable, but internal thermal energy is manifested as heat transfer due to temperature difference. It is argued here and elsewhere (related manuscript being finalized by this author) that heat (and anything else for that matter) could be transferred only if it exists as stored quantity in kind, in the first place. Therefore, thermal energy is stored heat (directly related to the system heat capacity), $U_{Th} \equiv Q_{Stored}$, and heat is the thermal energy transfer, $Q \equiv U_{Th,transfer}$. It is obvious and self-evident in caloric processes and quantified by the caloric quantities, i.e., system heat capacity and related properties [19].

In modern times, there is a tendency by some scientists to unduly discredit the ‘thermal energy’ as being indistinguishable from internal energy. However, the thermal heat capacity is well defined property and directly related to thermal energy. Denying existence of thermal energy is the same as denying existence of its transfer (heat transfer) [16,17,19]. Some others consider the Thermodynamic internal energy to be the thermal energy, although the former represents all energy types stored as the kinetic and potential energies of the constituent microstructure, namely, the thermal and mechanical elastic energies in simple compressible substances, in addition to the chemical and nuclear internal energies. In more complex system structures there may be more energy types. The stored system heat increases the system’s entropy and ‘thermal energy’, the latter is distinguished from the other internal-energy types, e.g., mechanical (elastic) energy. For example, the heating or compressing an ideal gas with the same amount of energy will result in the same temperatures and internal energies (the latter also equal for an elastic spring, for example), but it will result in different states, with different volumes and entropies, and similar for other material substances, see Fig. 2. It is reasoned here (and elsewhere by this author), that the thermal energy, as a system property, is distinguishable, regardless of its coupling with the other internal energy forms. A related manuscript is being finalized, to quantify the thermal energy within the system internal energy, see Fig. 2 [19].

2.1. Where does the ‘entransy’ fit in?

The new entransy concept and related analyses are inherently suited for heat transfer processes, without work interactions, called here ‘caloric processes’, but also provide certain advantages as a complementary approach for other processes in general, as discussed here. The entransy, as a new Thermodynamic function, related to heat and internal ‘thermal energy’ (the latter to be further developed) and relevant temperature, has its role to complement and clarify the elusive thermal phenomena with a potential to contribute in further optimization of thermal devices and processes. To better comprehend the concept and potential of entransy, it should be put in perspective and correlated with other concepts and many challenges in thermal physics. Some of those challenges will be discussed elsewhere and here. Richard Feynman once stated, “It is important to realize that in physics today, we have no knowledge what energy is.” This statement has a deeper meaning, since we tend to simplify, pre-judge, and proclaim definite meanings of the fundamental concepts, or to discredit new concepts. However, we have to keep our eyes and our minds open, and avoid premature judgements, especially of new and fundamental concepts.

3. Entransy concept and definitions

Entransy, a new thermo-physical quantity, based on “physical analogy between electrical conduction and heat conduction of heating an object (pure heat transfer - heating or cooling only),”

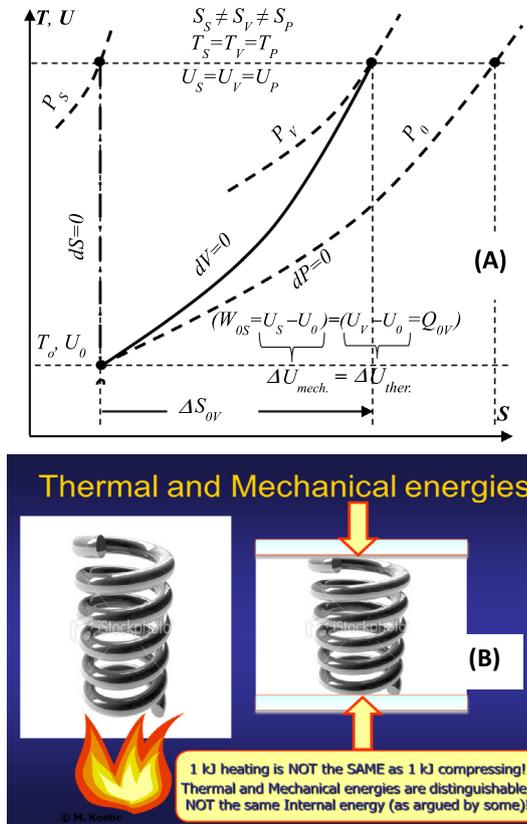


Fig. 2. Thermal and mechanical internal energies are distinguishable parts of the thermodynamic internal energy, the former increasing the thermal and latter the mechanical part of the internal energy, resulting in different states, regardless that the internal energies are the same, as illustrated by 1 kJ heating or 1 kJ compressing of ideal gas (A), or a spring (B).

has been introduced by a research group at Tsinghua University lead by Professor Guo, referred here as the Entransy authors. A descriptive concept of entransy, as well as entransy dissipation, but without using term ‘entransy’ was first proposed in 2003, which was called ‘heat transport potential capacity’, $Z_{tr} = QT/2 = MC_p T^2/2$, in the early publication [1], where term Q has represented ‘stored heat’ as a system quantity, as opposed to common heat transfer Q across a boundary surface. In a later 2007 publication [2] the name entransy was introduced as a state property,

$$E_{vh} = Q_{vh}T/2 = MC_v T^2/2 \tag{1}$$

Note the symbol Q_{vh} for stored heat with subscript ‘vh’ to differentiate it from the heat transfer Q . New quantity, *entransy*, was described as ‘heat transfer ability’ and ‘potential energy of thermal energy’, or ‘potential energy of heat’. The non-English speaking Entransy authors have been struggling to accurately define entransy, thus subjecting the concept to superficial confusion and even criticism. In subsequent publications, a new symbol ‘ G ’ for entransy has replaced E_{vh} , see related review and update [3]. Note also that entransy was derived as stored quantity for mass M and constant specific heat C_v , an unnecessary limitation, resulting in 1/2 constant in the expression after integration of $dG = Q_{vh}dT = (MC_v T)dT$ or $dG = TdQ_{vh} = Td(MC_v T)$, to be discussed later. This constant will be dropped when entransy concept-in-general is discussed here, and it is not necessary when heat is transferred or stored at constant temperature ($MC_v \gg 0$, then $G = QT$).

The physical analogy between electrical conduction, represented by the Ohm’s law, the electrical charge $Q_{ve} = I \cdot t = E_e/V$, and

heat conduction, is introduced as $Q_{vh} = Z_{tr}/T = E_{vh}/T = G/T$ (as concept-in-general, if electrical charge and heat are transferred at constant voltage and temperature, respectively), thus, in principle, defining a new physical quantity, entransy (for differential form, see Eq. (9)), i.e.:

$$G \equiv E_{vh} \equiv Z_{tr} = Q_{vh}T \tag{2}$$

Note that different symbols have been used in succeeding publication for the new quantity, entransy. Note also that notion of ‘stored heat’ (Q_{vh}), was used for stored heat within the material system, which is the case for common, constant volume processes ($Q = Q_{vh}$, both referred here as ‘thermal heat’), where change of stored internal energy U is equal to change of stored thermal energy $dU_{th} = dQ_{vt} = dU$. The same concept is also applied for definition of entransy rate and heat transfer rate. i.e.:

$$\dot{G} = (\dot{Q}) = \dot{Q}T \tag{3}$$

Since entransy is not conserved but dissipated (lost, destroyed) due to irreversibility, $\dot{G}_{Diss} = \dot{G}_{Loss}$, similarly to ‘exergy dissipation or loss’, the balance rate equation [2] (in latest notation) is:

$$\frac{dG}{dt} = \dot{G}_{Stored} = \dot{G}_{IN} - \dot{G}_{OUT} - \dot{G}_{Diss} \tag{4}$$

For 1-D steady-state heat conduction, Eq. (4) results in a simple and elegant expression, $\dot{G}_{Diss} = \dot{Q}(T_{IN} - T_{OUT})$. In differential form, entransy rate balance per unit of volume is:

$$\frac{dg}{dt} = -\nabla \cdot \dot{g} - \varphi_{Cd} \tag{5}$$

where $g = \frac{dG}{dV}$ is entransy point density (i.e., entransy per unit of differential volume), $\dot{g} = \frac{\partial \dot{G}}{\partial A}$ entransy flux, and $\varphi_{Cd} = \frac{d\dot{G}_{Loss}}{dV} = -\vec{g} \cdot \nabla T$, entransy dissipation function [2]. Then the entransy transfer efficiency is defined as:

$$\eta_G = \frac{\dot{G}_{OUT}}{\dot{G}_{IN}} = \frac{\dot{G}_{IN} - \dot{G}_{Diss}}{\dot{G}_{IN}} = 1 - \frac{\dot{G}_{Diss}}{\dot{G}_{IN}} \tag{6}$$

For 1-D steady-state heat conduction, Eq. (6) results in a simple and elegant expression,

$$\eta_G = 1 - \frac{\dot{G}_{Diss}}{\dot{G}_{IN}} = \frac{T_{OUT}}{T_{IN}} \tag{7}$$

The concept of new physical quantity, entransy G , represents functional-product of transferred or stored heat (Q or Q_{vh}) as heat or ‘thermal charge’ and absolute temperature as intensive thermal potential (T), the way electrical energy represents functional product of transferred or stored ‘electrical charge’ and voltage as intensive electrical potential. The analogy is complete for ‘pure heat transfer’ without any work conversion or dissipation, referred here as ‘caloric processes’, where thermal heat is conserved, as is electrical charge, while both are degraded to lower respective potentials. Additional complexity arises due to elusive nature of thermal energy which is self-evident but not yet completely defined and tabulated as property, as discussed in previous section and elsewhere.

This simple yet powerful analogy has deeper physical meaning than what it appears at first. It may contribute to better comprehension and analysis of thermal phenomena, regardless of initial confusions and deficiencies while developing the new concept. However, some distinction and uniqueness of entransy should be highlighted due to uniqueness and universality of thermal heat. The new physical quantity, entransy $G = Q_{vh}T$, which quantifies both, the thermal charge and its quality (heat and temperature, respectively), with SI unit [JK], is not energy, since thermal charge itself, Q_{vh} [J], is energy.

Therefore, the general concept of entransy, as product of thermal heat and temperature, is strongly physical and represents 'quantity and quality of thermal energy and its heat transfer' with [JK] SI-unit. Entransy transfer rate is equal to product of heat transfer rate and temperature, but entransy property is defined as half of product of "stored heat" and temperature [1–3] due to lack of quantification of thermal energy within internal energy of the system. Unfortunately and unnecessarily, the stored heat is defined for constant specific heat case, as will be discussed later.

Similar to the enthalpy and free energy, the entransy has inherent advantage over exergy since it represents quality of thermal energy without any need for reference dead state (T_0, P_0). At the same time, it has inherent disadvantages, like enthalpy and free energy, that they are directly superior for certain processes but not for all. Entransy is what it is, as is defined, and any subjective praise or criticism is unnecessary, misleading and thus unjustified. The use of entransy in analysis and optimization of thermal and other energy processes is up to comprehension and creativity of the researchers who choose to use it. Entransy concept and applications are still being developed and objective criticism will contribute to its further comprehension and utility.

4. Entransy challenges and controversy

As already stated, the Entransy authors, have introduced the new concept [1] later named *entransy* [2] and followed by a series of related publications, e.g. [3] and elsewhere. The related disputes and controversies started by a "Letter to the Editor [4]" by Professor Bejan and Lorente charging that a paper published by Professor Guo et al. is plagiarism of their prior work. The rebuttal, with response to accusation, was published in [10]. Afterwards, the Entransy concept and approach have been challenged and criticized by several authors, referred here as Criticizers, in a series of papers [5–9], triggering published rebuttals by the Entransy authors [11–13], also summarized in [14].

Objectively judging a new concept is challenging and requires comprehensive and critical analysis by many, over a long time. In developing stages, every new concept will exhibit inherited deficiencies along with its benefits. Therefore, the purpose of this article is to provide limited scrutiny of the entransy concept and some prejudices of the Criticizers without challenging their motives, the later to be left to the wider audience.

The entransy concept, while still in development and with certain deficiencies, has been challenged and discredited by the Criticizers, some including 'strong' statements, bordering with proclamation with accusations. For example, Professor Bejan [6] stated that "entransy has no meaning in physics... rests on the false claims... with every new 'entransy' paper we are reminded that entransy is a hoax... follows this template: copy, translate, and publish." Bejan further claims that "Entransy has no meaning in physics, because, at bottom, it rests on the false claim that in order to transfer heat to a solid body of thermodynamic temperature T , the heat transfer must be proportional to T . Entransy 'dissipation' is a number proportional to well-known measures of irreversibility such as entropy generation and lost exergy (destroyed available work). The broader trend illustrated by the entransy hoax is that it is becoming easy to take an existing idea, change the keywords, and publish it as new." Those are incomplete, misleading and questionable statements, with unusually strong wording, particularly from a renowned scientist, and may have some daring motivation. Claiming that entransy has no physical meaning and its "arbitrariness of this kind is striking" is subjective and far from justified. Internal energy, $u = C_v T$, is simply defined as a concept if $C_v = \text{constant}$, regardless that it is not. Bejan even claims that the entransy analogy is "false trick," even though the analogy is obvious and

physical, as clearly stated by Guo et al. [1–3], including the published rebuttal, with response to 'allegations' [11]. Although I agree that nowadays "many write and few reads," but Bejan's claim is again extreme, "everybody writes and nobody reads." This publication trend is general and is not the proper reason to criticize and dismiss entransy, outright, without due objective and holistic analysis of its disadvantages but also advantages. Bejan incorrectly claimed that the term T^2 in entransy is introduced arbitrarily, and further claimed that similar analysis could be reproduced for any T^n as a 'modified entransy' to republish existing literature. That is not true since T^2 comes from simplified definition of entransy transfer (QT) and entransy property ($UT = mC_v T \cdot T = \text{const} \cdot T^2$, based on physical analogy with electrical charge and other flux transfers and stored 'charges'. The constant specific heat C_v , may represent the average specific heat for the relevant temperature range, but that restriction or deficiency is not critical for the physical meaning of the entransy analogy as clearly presented by the Entransy authors.

Grazzini et al. [5] stated that, "analysis shows that entransy does not contain any new information in comparison with a classical thermodynamic analysis of systems. Furthermore, they claim that entransy dissipation analysis is a duplicate of entropy generation analysis." These are subjective judgements and as such may equally imply to many other derived physical quantities, like enthalpy, free energy, or exergy. But then the full comprehension is overlooked. Full thermodynamic analysis may be conducted with internal energy U , and P and V terms, but enthalpy $H = U + PV$ has advantage to synergize the quantities for constant pressure and flow processes. Similarly, there are Thermodynamics' textbooks that perform full 'useful work-potential' analysis based on entropy generation and irreversible work loss, but without mentioning 'exergy' as a new concept or a term. Furthermore, the Helmholtz and Gibbs' free energies, $F = U - TS$, or $F_G = H - TS = U + PV - TS$ are derived from other established quantities and may be prejudged as redundant, but they have their unique meanings for special processes, e.g., for constant volume-temperature or constant pressure-temperature processes, respectively, among others.

Then some other authors follow the prior Criticizers to discredit the entransy without due rigor of objective and all-inclusive analysis of positives and negatives of a newly developing concept. Herwig [7] claims that "entransy is not extension of the well-established theory of heat transfer not consistent with this classical approach; and that there is no real need for the extension of the classical theory by introducing entransy as a quantity that was missing in the past." Many of the claims to discredit entransy (see also below) have the same problems, are subjective and not all-inclusive and substantive, thus incomprehensive. The rebuttal, with response to the challenges, was published in [12]. I would further argue and reason that these claims are selective and debatable, reflecting the human nature to reject novelty before it is fully comprehended.

And then comes Award [8] to join the Criticizers, to eagerly second the predecessors that "entransy is improper and not needed," proclaiming in his title, "Entransy is Now Clear." Not so simple, and not so fast! In Award's words, "claim that entransy is a state quantity because it is a function of temperature, just like internal energy is a clear violation of thermodynamics. Energy change (not 'energy') is an extensive property." Since when 'energy' is not an extensive property? An extensive property, like energy, is an integral 'stored charge' or extensive potential sustainable and defined in an equilibrium state, without any need for "change." The energy change is taking place during a process due to its flux through the system boundary ($dU = \delta Q + \delta W$). Then, Award restates other claims from the Criticizers by proclamation without due justification, and endorses Bejan's paper [6] as "a highly recommended

read.” The rebuttal, with response to Award’s challenges, was published in [13]. Furthermore, I do not see much of reasoning in [8] but lack of due objectivity and comprehension. The claim that by reducing the temperature difference to zero ceases the heat transfer and becomes meaningless, is not accurate, for example for the Carnot cycle and all reversible processes. In such limiting, ideal processes the temperature difference will be reduced to infinitesimally small value but heat transfer will be arbitrarily finite if thermal resistance is infinitesimally small or heat transfer area infinitely large.

Sekulic et al. [9] title their paper, “Entransy: a misleading concept for the analysis and optimization of thermal systems.” Furthermore, they state, “We have identified shortcomings of the entransy approach, including the apparently extremely small niche of very limited importance claimed for entransy by its advocates and the impracticality of results elicited using entransy.” However, it is well known that optimization of thermal systems is inherently complex and ambiguous, and often controversial. In general, the ‘extrema principles’, the minimum and maximum entropy production principles (or entransy dissipation principles), are both elusive and not yet fully understood. Furthermore, in heat exchangers and other thermal systems, the entransy and exergy are dissipated, and entropy is generated, all being directly correlated. With an objective to increase heat transfer, everything else being the same, reducing entransy or exergy dissipation, i.e., entropy generation due to heat transfer, may be undesirable and counterproductive for the device performance if such measure is not utilized for heat to work conversion, but the irreversible losses are merely relocated outside of the system [18]. In particular, a reduction in irreversibility does not always correspond to the best performance of thermal devices or systems. The Second Law of Thermodynamics, and the entransy, exergy and entropy that quantifies its analysis, are sometimes subtle and thus may be confusing and misleading if not fully understood and properly accounted for, to enhance the efficacy of all devices involved in all processes to be optimized. Sekulic et al. [9] further stated that “Other observers have pointed out additional entransy shortcomings. While we are in solidarity with the authors of these references in their doubts about entransy, we are hesitant to endorse all that each has written on the subject, and leave it to readers to navigate and rationalize the various points of view expressed.” They [9] even imply that “the Entransy authors, by titling their publication, ‘Controversy about Entransy Theory’ [14], explicitly recognize that entransy is controversial . . . We fully agree with that self-assessment.” That is obviously misleading, since the authors [14] used title “Entransy Controversy” to refute the Criticizers, and not to agree with them. As always, the comprehensive and objective judgement will be left to be formed in due time by including much wider scientific community.

5. Entransy deficiencies, discussions and suggestions

The Entransy authors have been struggling to assign precise definition for entransy as illustrated by confusing definitions during the new concept development. The confusing or even misleading language terminology could and should be improved, but should not in any way diminish the fundamental meaning of the new entransy concept as otherwise presented by the Entransy authors, nor it should be used *per se* by others to unjustifiably discredit the true meaning of the new concept.

Unnecessary confusions have been produced by the Entransy authors due to perplexing and somewhat misleading description and language ambiguities, especially when defining a new concept by non-native-language authors. For example, “heat transport potential capacity” and “heat transfer ability” are ambiguous, and “potential energy of thermal energy” and “potential energy of heat”

are misleading, since new quantity does not have energy unit. There is even an inherent difficulty to completely define known thermal phenomena and quantities due to existing inconsistencies. Language terminology is not precise in general and especially as the second language describing new concepts. For example, the term “potential” has many meanings in physics depending on attributes used and context usage. For example, “thermal potential” often refers to intensive quantity like temperature, but also may refer to an extensive quantity like stored heat or energy, or “work potential” for exergy, as in mainstream Thermodynamics textbooks. It even may have other meanings.

The Entransy authors have also attempted to simplify and generalize the new concept, including somewhat confusing and imprecise definitions. Under the criticism, they impose some unnecessary limitations, or sometimes justifying the new concept with far-fetched and misleading but unnecessary statements, like associating entransy with “thermal potential and viriational invariant introduced by Biot and summarized by Eckert and Drake” [2], or stating that “entransy possess the nature of the potential energy of the phonon gas (thermomass)” [3]. Additionally, the Entransy authors have tried to emphasize differences between entransy, entropy and exergy, and draw some premature and unnecessary justifications and conclusions. These quantities are directly correlated since all three quantify the thermal irreversibility in different ways, and have their inherited advantages and disadvantages, by describing/quantifying irreversible processes in different ways. Furthermore, each and all of these quantities, including entransy, have unique potential to help better comprehend the subtle thermal concepts and phenomena within an elusive thermal landscape.

Entransy dissipation or entransy loss, correlated with work loss or exergy dissipation and entropy generation, due to temperature differences and heat fluxes, represents the loss of the ‘Carnot’s work-potential’, and may or may be less important in many flow and heat transfer processes, due to the fact that heat transfer is, by its nature, a typical irreversible process. Furthermore, if substantial entransy dissipation is due to extreme non-uniformity of temperature fields, driven by high heat fluxes, the consideration of alternate device design to utilize the Carnot’s work potential may be considered if it is feasible and economical [18]. For example, see Fig. 3, for 1-D steady-state heat conduction, caloric process 1–2 (conserved thermal heat $Q = \text{constant}$), we have entransy G , decreasing linearly with temperature T , thus defining entransy dissipation or loss, $G_{LOSS} = Q\Delta T = S_{gen}T_2T_1$, being directly related with exergy loss, $EX_{LOSS} = W_{LOSS} = S_1\Delta T = (Q/T_1) \Delta T = S_{gen}T_2 = G_{LOSS}/T_1$. This simple thermal process illustrates correlations between relevant quantities and their potential utilities.

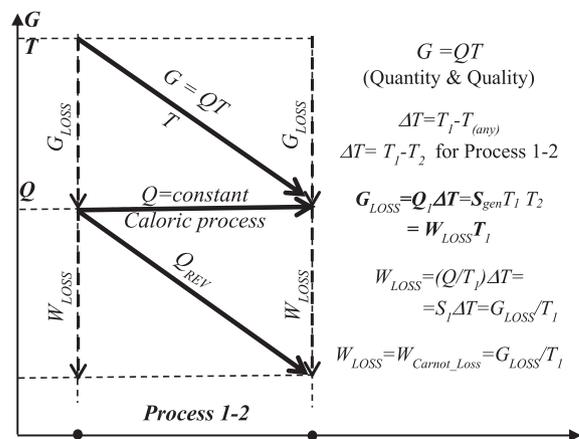


Fig. 3. Correlation between entransy G , reversible heat Q_{REV} , entransy dissipation or loss G_{LOSS} , and Carnot work-potential loss W_{LOSS} , during 1-D steady-state heat conduction caloric process 1–2 with conserved heat transfer Q .

Therefore, the entransy is directly related to exergy and entropy, and irreversible entransy-loss is directly related to work-potential loss or exergy-loss, and entropy-generation. However, the three concepts are not exclusive nor complementary but directly related, with their own inherited advantages and disadvantages, the way entropy, free energy and Gibbs free energy functions are, or the way internal energy and enthalpy are. Note that all above quantities, except exergy, are state functions, i.e., state properties as combinations of other state properties. The entransy is more similar to exergy than entropy, since it describes quantity and quality of thermal heat, but is ‘extended’ property function similar to enthalpy and free energy which are not always conserved, but very fundamental in their own rights. However, the entropy, as thermal displacement property, is different type of property, similar to volume displacement, but both are directly and strongly related to all other properties.

The entransy has been defined as a state property, as a function of ‘stored heat’, and regrettably and unnecessarily restricted for constant specific heat systems [2] (see Eq. (1)), although the real system specific heat is function of temperature. It is suggested that entransy be defined instead, as integral quantity for variable specific heat for incompressible systems and/or constant volume processes $C_v = f(P,T) \approx f(T)$, i.e.,

$$G = \int MC_v TdT \tag{8}$$

There is a need for further clarifications of the entransy concept and possible refinements.

Entransy, as an extensive, thermal potential with [JK] SI unit, and its differential, are:

$$G = TQ; \quad dG = d(TQ) = \underbrace{TdQ}_{System} + \underbrace{QdT}_{Flow} \tag{9}$$

The above is similar to the ‘work functional potential’ (W_{FP}) and ‘heat functional potential’, and their differentials, both used in Enthalpy ($H = U + PV$) and Gibbs free energy $F_G = U + PV - TS$, for example (see Table 1):

$$W_{FP} = PV; \quad dW_{FP} = d(PV) = \underbrace{PdV}_{System} + \underbrace{VdP}_{Flow} \tag{10}$$

$$Q_{FP} = TS; \quad dQ_{FP} = d(TS) = \underbrace{TdS}_{System} + \underbrace{SdT}_{Flow} \tag{11}$$

Alternative, entransy functional potential (subscript ‘FP’) could be defined based on the ‘heat functional potential’ Q_{FP} , i.e.,

$$G_{FP} = TQ_{FP} = T(TS) = T^2S; \quad dG_{FP} = d(T^2S) = \underbrace{T^2dS}_{System} + \underbrace{2STdT}_{Flow} \tag{12}$$

Note that $G_{FP} \neq G$, the way the entropy functional potential, $S_{FP} \equiv (U + PV - \sum \mu_i N_i)/T \neq S$, is not equal to entropy, as well as $W_{FP} \neq (W = \int PdV)$, and $Q_{FP} \neq (Q = \int TdS)$ (see Table 1).

If and after the thermal energy U_{Th} is fully defined and quantified, the entransy could be naturally defined as:

$$G = TU_{Th} = TQ_{Stored} \tag{13}$$

At the present time, since the thermal energy is not fully quantified, it is proposed that entransy be simply defined based on thermodynamic internal energy U , as:

$$G = TU \tag{14}$$

Note that $U = U_{Th}$ for incompressible systems and/or constant volume processes, so Eq. (14) reduces to Eq. (13).

Furthermore, the entransy of work, G_W , is also necessary to be defined for processes when thermal heat is converted to work, like in heat engines. It could be defined from the reversible, Carnot

Table 1

Common thermodynamic potentials or functional potentials (subscript ‘FP’), including proposed Entransy functional potential G_{FP} .

Name	Symbol	Formula	Natural variables
Internal energy	U	$U = \int(TdS - PdV + \mu_i dN_i)$	S, V, N_i
Work functional potential	W_{FP}	$W_{FP} = PV$	V
Enthalpy	H	$H = U + PV$	S, P, N_i
Heat functional potential	Q_{FP}	$Q_{FP} = TS$	S
Helmholtz Free energy	F, A	$F = U - TS$	T, V, N_i
Gibbs Free energy	F_G	$F_G = (U + PV) - TS$	T, P, N_i
Landau (Grand) potential	Ω, Φ_G	$\Omega = U - TS - \mu_i N_i$	T, V, μ_i
Entropy functional potential	S_{FP}	$S_{FP} = (U + PV - \mu_i N_i)/T$	T, P, μ_i
Entransy	G	$G = TQ_{Sys}$	T, S
Entransy functional potential	G_{FP}	$G_{FP} = TQ_{FP} = T^2 S$	T, S

NOTE 1: Natural variables: T = temperature, S = entropy, P = pressure, V = volume. For completeness, μ_i = chemical potential and N_i = mole number, are used as natural variables.

NOTE 2: Work $W = \int PdV$, with V as space displacement, and heat $Q = \int TdS$, with S as thermal displacement.

NOTE 3: $G_{FP} \neq G$ (not equal to entransy); $S_{FP} \neq S$ (not equal to entropy); $W_{FP} \neq W$ (not equal to work); and $Q_{FP} \neq Q$ (not equal to heat).

cycle correlation, using the entransy balance (Eq. (4)), and considering that there is no entransy loss in an ideal reversible process, i.e., $G_{IN} = G_{OUT}$ or $G_1 = G_W + G_2$. Using notation on Fig. 1, we have,

$$G_W = G_1 - G_2 = G_1[1 - (T_2^2/T_1^2)] \text{ or } dG_W = [1 - (T_2^2/T_1^2)]dG_1 \tag{15}$$

In another publication [20] (with rebuttal [21]), the work entransy, G_W , was derived by algebraic manipulation as $G_W = WT_1 = (Q_1 - Q_2)T_1 = Q_1(T_1 - T_2)$. However, this definition is not appropriate since it does not satisfy condition that entransy loss is zero for reversible processes, as Eq. (15) does.

The above discussions from many different facets, including suggestions and recommendations, do illustrate and demonstrate the need for further clarification and development of the new entransy concept.

6. Conclusions

The physics behind the *entransy* concept is highlighted here from another perspective, since it was somehow ‘missed’ by several authors who were trying to discredit its meaning and usefulness. As already stated, the entransy is a very logical and physical concept, based on the analogy between heat conduction and electrical conduction, as well as other similar concepts in physics, but not available in thermal science, until it was introduced in early 2000’s. Since entransy combines thermal heat with its temperature potential, it includes both, the quantity and quality of heat and thermal energy. Entransy concept and controversy are also put in perspective with regards to still-elusive nature and many open issues in thermal physics.

The entransy has been used for analysis and optimization of a number of heat transfer systems and processes, as described in many publications since its introduction. Regrettably, the group which introduced and has been promoting the new concept, on occasions misconstrued and over-stretched its accurate meaning and utility, and unnecessarily contributed to certain confusions and controversies. However, any deficiency related to the development of entransy concept should not diminish its underlying importance and future potential. Even the greatest concepts in science history were accompanied with some fundamental mistakes, like *caloric* and *Carnot’s* theories, among others. The caloric was mistakenly considered as conserved quantity, and Sadi Carnot reasoned the heat engine processes based on analogy of heat-engines with the water-wheels, and laid foundations for others to develop Thermodynamics, regardless that his reasoning of

conservation of caloric violated the energy conservation concept not known at his time. Similarly, the deficiencies accompanied the development of *entransy* should not diminish its underlying concept, importance and future potential.

Since *entransy* represents both, the quantity and quality of heat, i.e., synergy of stored thermal heat and its temperature level, it is related to exergy and free energy, in turn all related to entropy, all with different units and physical meanings. But *entransy* has a unique advantage to be a true state property while exergy is not since it also depends on reference, surrounding dead state. Alternative quantities and methodologies do have inherited advantages and disadvantages and thus are useful to better analyze and comprehend the elusive thermal phenomena.

The *entransy* concept, while still in development and with certain deficiencies, has been lately challenged and criticized by several publications, as “inconsistent and not needed, having lack of content in physics, redundant to entropy,” among others, thus creating controversies, that have been put here in broader, including historical and contemporary perspective, with regards to still-elusive nature and many open issues in thermal physics. It appears that some ‘harsh’ criticism, without due rigor of impartial and all-inclusive analysis of positives and negatives of a newly developing concept, is not justified. Objectively judging a new concept is challenging and requires comprehensive and critical analysis by many, over a long time.

Regardless of its redundancy, being derived from other physical quantities, as are also enthalpy, exergy and free energy, for example, it does not diminish *entransy* uniqueness and usefulness in thermal analysis and optimization. Actually, the *entransy*, due to its unique nature, may contribute to better comprehension of often obscured thermal phenomena. After all, it is useful to look at phenomena and processes from another perspective, like using frequency domain to see differently the time domain of certain phenomena. The claim that there is no real need for *entransy* is subjective and without due justification. It would be like to claim that we do not need enthalpy ($H = U + PV$) or the Gibbs free energy function ($F_G = H - TS = U + PV - TS$) just because they are combined functions of already well-established properties, U , P , V , T , and S . Of course, we could do relevant thermal analysis using state properties, u , P , v , T and s , but enthalpy has its advantages for analysis of isobaric and flow processes, the way Gibbs function is convenient for analysis of isobaric-isothermal processes, among others. And as such, they, including *entransy*, are consistent with other properties and have physical meaning, regardless how elusive or not easily comprehensible.

Nature is, and so is *entransy*, what it is, no more and no less. Any subjective praise or criticism is unnecessary, and sometimes misleading and thus unjustified. The use of *entransy* in analysis and optimization of thermal and other energy processes is up to comprehension and creativity of the researchers who choose to use it. *Entransy* concept and applications are still being developed and objective criticism will contribute to its further comprehension and utility. Even if *entransy* has been hyped-up in the past, it would be a mistake to hype it down now, based on limited and

prejudice claims, since innovative and alternative concepts are useful to clarify the elusive and confusing thermal landscape. Regardless of deficiencies during the new concept development and the need for further clarifications and improvements, it would be premature and unjust to discredit it based on limited and subjective evaluation, as if the ‘already established’ concepts and methodologies are perfect and do not need alternatives and innovations, as if further progress is not needed.

Conflict of interest

The authors declare that there are no conflicts of interest.

References

- [1] Z.Y. Guo, X.G. Cheng, Z.Z. Xia, Least dissipation principle of heat transport potential capacity and its application in heat conduction optimization, *Chin. Sci. Bull.* 48 (4) (2003) 406–410.
- [2] Z.Y. Guo, H.Y. Zhu, X.G. Liang, *Entransy* – a physical quantity describing heat transfer ability, *Intrn. J. Heat Mass Transfer (IJHMT)*, vol. 50, 2007, pp. 2545–2556.
- [3] Q. Chen, X.G. Liang, Z.Y. Guo, *Entransy* theory for the optimization of heat transfer – a review and update, *Intrn. J. Heat Mass Transfer (IJHMT)*, vol. 63, 2013, pp. 65–81.
- [4] A. Bejan, S. Lorente, Letter to the editor, *Chem. Eng. Process.: Process Intensification* 56 (2012).
- [5] G. Grazzini, R. Borchellini, U. Lucia, Entropy versus *entransy*, *J. Non-Equilib. Thermodynam.* 38 (2013) 250–271.
- [6] A. Bejan, *Entransy*, and its lack of content in physics, *J. Heat Transf.* 136 (5) (2014) 055501.
- [7] H. Herwig, Do we really need ‘*entransy*’? A critical assessment of a new quantity in heat transfer analysis, *J. Heat Transf.* 136 (4) (2014) 045501–045503.
- [8] M.M. Awad, Discussion: *entransy* is now clear, *J. Heat Transf.* 136 (9) (2014) 095502.
- [9] D.P. Sekulic, E. Sciuabba, M.J. Moran, *Entransy*: a misleading concept for the analysis and optimization of thermal systems, *Energy* 80 (2015) 251–253.
- [10] X.B. Liu, Q. Chen, M.R. Wang, N. Pan, Z.Y. Guo, Reply to letter to the Editor, *Chem. Eng. Process.* 56 (2012) 35–36.
- [11] Z.Y. Guo, Closure to “Discussion of ‘*Entransy*,’ and Its Lack of Content in Physics’”, *J. Heat Transf.* 136 (5) (2014) 056001.
- [12] Z.Y. Guo, Q. Chen, X.G. Liang, Closure to “Discussion of ‘Do We Really Need ‘*Entransy*’?””, *J. Heat Transf.* 136 (4) (2014) 046001.
- [13] Q. Chen, Z.Y. Guo, X.G. Liang, Closure to “Discussion of ‘*Entransy* is Now Clear’”, *J. Heat Transf.* 136 (9) (2014) 096001–096011.
- [14] Z.-Y. Guo, X.-G. Liang, Q. Chen, Controversy about *entransy* theory.” Beijing, China: Institute of Engineering Thermophysics, Department of Engineering Mechanics, Tsinghua University; June 2015.
- [15] M. Kostic, Irreversibility and Reversible Heat Transfer: The Quest and Nature of Energy and Entropy,” IMECE2004, ASME Proceedings, ASME, New York, 2004 (PDF).
- [16] M. Kostic, Revisiting the Second Law of Energy Degradation and Entropy Generation: From Sadi Carnot’s Ingenious Reasoning to Holistic Generalization, in: AIP Conf. Proc., vol. 1411, 2011, pp. 327–350. doi:10.1063/1.3665247.
- [17] M. Kostic, The elusive nature of entropy and its physical meaning, *Entropy* 16 (2) (2014) 953–967, <http://dx.doi.org/10.3390/e16020953>.
- [18] M.M. Kostic, Entropy Generation Results of Convenience But without Purposeful Analysis and Due Comprehension—Editorial, *Entropy*, vol. 18(1), 2016, pp. 28. doi:10.3390/e18010028.
- [19] Kostic, M. “Reflections on Caloric Theory and Thermal Energy,” Northern Illinois University, (accessed 2017). <http://niu.edu/kostic/_pdfs/reflections-caloric-theory-thermal-energy.pdf>.
- [20] M. Xu, The thermodynamic basis of *entransy* and *entransy* dissipation, *Energy* 36 (7) (2011) 4272–4277.
- [21] Z.Y. Guo, Comments on “The thermodynamic basis of *entransy* and *entransy* dissipation” [*Energy* 36, 4272–4277], *Energy* 68 (2014) (2011) 998–999.