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IRREVERSIBILITY AND REVERSIBLE HEAT TRANSFER: *The Quest and Nature of Energy and Entropy*

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ABSTRACT

This paper focuses on philosophical and practical aspects of energy and entropy, with emphasis on reversibility and irreversibility, and a goal to establish the concept of "reversible heat transfer," regardless that heat transfer is a typical irreversible process. Heat transfer, like any other energy transfer, may be achieved from any-to-any temperature level, and in limit be reversible, if temperature of an intermediary cyclic substance is adjusted as needed, using isentropic compression and expansion. The reversible heat transfer limits are the most efficient and demonstrate limiting potentials for practical heat transfer processes.

NOMENCLATURE

0	surroundings
1	initial state
2	final state
COP	coefficient of performance
CPC	cogeneration power cycle
H	system at higher temperature
HPC	heat pump cycle
L	system at lower temperature
m	mass
P	energy potential, like pressure, temperature, voltage, etc.
PC	power cycle,
PHP	dual power-heat pump cycle
Q	heat as energy transfer
R	refrigeration
R	heat transfer reservoir (system)
S	entropy
ΔS	entropy change magnitude (absolute value)
S	system
S_G	entropy generation
T	temperature
U	internal thermal energy
W	work as energy transfer

1. INTRODUCTION: *Energy and Entropy*

This paper has an objective to emphasize known, but not so well-recognized issues about entropy, irreversibility and reversibility, as well as to put certain physical and philosophical concepts in perspective, and initiate discussion and arguments about the paper theme. The paper focuses on practical aspects of energy and entropy, with emphasis on reversibility and irreversibility, and a goal to establish the concept of "*reversible heat transfer*," regardless that heat transfer is a typical irreversible process. Energy is a fundamental concept indivisible from matter and space, and energy exchanges or transfers are associated with all processes (or changes), thus indivisible from time. Actually, energy is "the building block" and fundamental property of matter and space, thus fundamental property of existence. Energy transfer is needed to produce a process to change other properties. Also, among all properties, the energy is the only one which could be converted to mass and vice versa: $E=mc^2$ (known in some literature as "mass energy"). Any and all changes (happening in time) are caused by energy exchanges or transfers from one substance (*system* or *subsystem*) to another. A part of a system may be considered as a subsystem if energy transfer within a system is taking place, and inversely, a group of interacting systems may be considered as a larger isolating system, if they do not interact with the rest of the surroundings. There are many types of energy [1-6], all of which could be classified as microscopic (or internal within a system microstructure) and/or macroscopic (or external as related to the system as a whole with reference to other systems). Furthermore, energy may be "quasi-potential" (associated with a system equilibrium state and structure, i.e. system property) or "quasi-kinetic" (energy in-transfer from one system or one structure to another, in form of work or heat) [6].

Energy transfer may be in organized direction (work transfer) or in chaotic disorganized form (heat transfer). Energy transfer into a system builds up energy-potential (called simply potential for short, like pressure, temperature, voltage, etc.) over energy displacement (like volume, entropy, etc.); and vice versa. If energy is transferred from a system, its energy potential (and often displacement) are decreased, which reflects the fact that energy is transferred from higher to lower energy potential only. Every organized kinetic energy will, in part or in whole (and ultimately in whole), disorganize/dissipate within microstructure of a system (over its mass and space) into disorganized thermal energy. Entropy, as energy-displacement system property, represents the measure of energy disorganization. Contrary to energy and mass, which are conserved in universe, the entropy is continuously generated (increased) due to continuous disorganization of energy in transfer ('expansion' of energy towards and over lower potentials). Often, we want to extract energy from one system in order to purposefully change another system, thus to transfer energy in organized form (as work). No wonder that energy is defined as "ability to perform work," and a special quantity "exergy" is defined as the maximum possible work that may be obtained from a system in a process by bringing it to equilibrium with reference surroundings. The maximum possible work will be obtained if we prevent energy disorganization, thus using limiting reversible processes. Since the energy is conserved during any process, only in ideal reversible processes the entropy (measure of energy disorganization) and exergy (maximum possible work with reference to the surroundings) will be conserved, while in real irreversible processes, the entropy will be generated and exergy will be partly (or even fully) destroyed.

Therefore, heat transfer and thermal energy are universal manifestation of all natural and artificial (man-made) processes, where organized quasi-kinetic energies are disorganized or dissipated as thermal energy in irreversible and spontaneous processes. Regardless that heat transfer is a typical irreversible process, in the direction from higher to lower thermal potential (temperature), it is possible to change the temperature level using adiabatic (without heat transfer) compression or expansion processes, thus significantly reducing irreversibility and, in limit, provide reversible heat transfer between any temperature levels, even from lower to higher temperature. This is practically demonstrated in refrigeration and heat pump devices, and enables further increase in energy efficiency. A dual power-and-heat-pump cycle is introduced and analyzed here, to provide for reversible heat transfer. It may be considered as a reversible heat-transfer transformer, from-any-to-any temperature levels

2. REVERSIBILITY AND IRREVERSIBILITY:

Energy Transfer and Disorganization, Rate and Time, and Entropy Generation

Energy transfer (when energy moves from one system or subsystem to another) through a system boundary and in time, is of kinetic nature, and may be directionally organized as work or directionally chaotic and disorganized as heat. However, the net-energy transfer is in one direction only, from higher to lower energy-potential, and the process cannot be reversed. Thus *all real processes are irreversible* in the direction of decreasing energy-potential (like pressure and temperature) and increasing energy-displacement (like volume and entropy) as a consequence of energy and mass conservation in the universe. This implies that universe (as isolated and unrestricted system) is expending with entropy generation (or increase) as a measure of continuous energy disorganization. However, in limit, it is possible to have an energy transfer process with infinitesimal potential difference (still from higher to infinitesimally lower potential, P). Then, if infinitesimal change of potential difference direction is reversed ($P+dp \rightarrow P-dP$, with infinitesimally small external energy, since $dP \rightarrow 0$), the process will be reversed too, which is characterized with infinitesimal entropy generation, and in limit, without energy degradation (no further energy disorganization) and no entropy generation -- thus achieving a limiting reversible process. Such processes at infinitesimal potential differences and rates, allow system equilibrium at any instant but with incremental changes in time, are called quasiequilibrium processes. Only quasiequilibrium processes are reversible and vice versa. In effect, the quasiequilibrium reversible processes are infinitely slow processes at infinitesimally small potential differences, but they could be reversed to any previous and forwarded to any future equilibrium state, without any 'relevant effect' on the involved systems, thus without 'permanent change.' Therefore, the changes are 'fully reversible,' and along with their rate of change and time, totally irrelevant, as if nothing is effectively changing (no permanent-effect to the surroundings or universe) – the time is irrelevant as if it does not exist, since it could be reversed or forwarded at will and at no 'cost' (no permanent change and, thus, relativity of time). Because the real time cannot be reversed, it is a measure of permanent changes, like irreversibility, which is in turn measured by entropy generation. In this regard the time and entropy generation of the universe have to be related.

Entropy is also a system property, which together with energy defines its equilibrium state, and actually represents the system energy-displacement or random energy disorganization/dissipation over its mass and space it occupies. Therefore, the entropy of a system for a given state is the same regardless whether it is reached by reversible heat transfer or irreversible heat or irreversible work transfer. For example, an ideal-gas system entropy increase will be the same during a reversible isothermal heat transfer and reversible expansion to a lower pressure (heat-in equal to expansion work-out), as during an irreversible adiabatic unrestricted expansion (no heat transfer and no expansion work) to the same pressure and volume, as illustrated in Fig. 1a & 1b respectively.

If heat or work at higher potential (temperature or pressure) than necessary, is transferred to a system, the energy at excess potential will dissipate spontaneously to a lower potential (if left alone) before new equilibrium state is reached, with overall entropy generation, i.e. increase of entropy displacement over a lower potential. A system will 'accept' energy at minimum necessary (infinitesimally higher) or higher potential. Furthermore, the higher potential energy will dissipate and entropy increase will be the same as with minimum necessary potential. However, the source entropy will decrease to a smaller extent over higher potential, thus resulting in overall entropy generation for the two interacting systems,

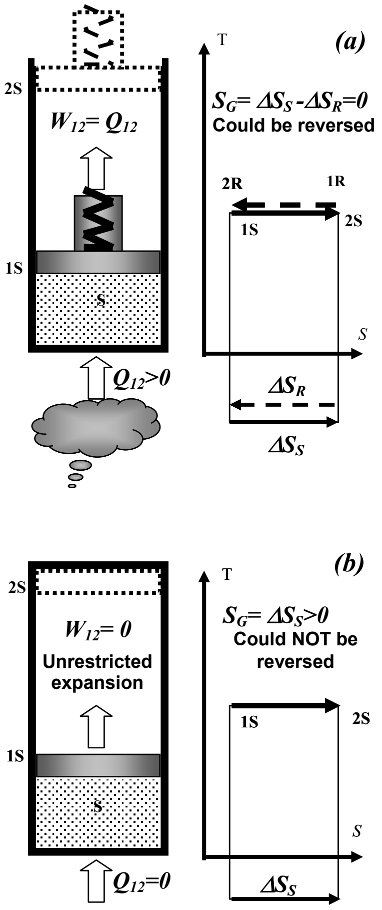

FIGURE 1: (a) Isothermal reversible heat transfer and restricted reversible expansion; (b) adiabatic unrestricted irreversible expansion of the same initial system to the same final state.

which may be considered as a combined isolated system (no energy exchange with the rest of the surroundings). The same is true for energy exchange between different system parts (could be considered as subsystems) at different energy potentials (non uniform, not at equilibrium at a given time). Energy at higher potential (say close to boundary within a system) will dissipate (mix) to parts at lower energy potential with larger entropy increase than decrease at higher potential, resulting in internal irreversibility and entropy generation, i.e. energy 'expansion' over more mass and/or space with lower potential. Therefore, entropy is not displacement for heat only, as often stated, but also displacement for any energy 'expansion with disorganization' and the measure of irreversibility. Examples are unrestricted or throttling expansion with no heat exchange but entropy generation. Therefore, entropy generation is fundamental measure of irreversibility or 'permanent changes,' i.e. a measure of the net-effect within the universe, which can not be reversed.

Even though, directionally organized energy transfer as work, does not possesses or generate any entropy (no energy disorganization), it is possible to obtain work from the equal amount of disorganized thermal energy or heat, if such process is reversible. There are two typical reversible processes where disorganized heat or thermal energy could be entirely transferred into organized work, and vice versa. Namely, they are:

(1) reversible expansion at constant internal energy, e.g. isothermal ideal-gas expansion, ($\delta W=\delta Q$), Fig. 1a, and

(2) reversible adiabatic expansion ($\delta W=-dU$).

During a reversible isothermal heat transfer and expansion of an ideal-gas system (S), for example, Figure 1a, the heat transferred from a thermal reservoir (R) will reduce its entropy for (ΔS_R magnitude) wile ideal gas expansion in space (larger volume and lower pressure) will further disorganize its internal thermal energy and increase the gas entropy for (ΔS_S). In the process an organized expansion work, equivalent to the heat transferred, will be obtained ($W_{12}=Q_{12}$). The process could be reversed, thus it is reversible process with zero total entropy generation ($S_G=\Delta S_S-\Delta S_R=0$). On the other hand, if the same initial system (ideal gas) is expanded without any restriction (Fig. 1b, thus zero expansion work) to the same final state, but without heat transfer, the system internal energy will remain the same but more disorganized over the larger volume, resulting in the same entropy increase as during the reversible isothermal heating and restricted expansion. However, this process can not be reversed without 'external work,' since no work was obtained to compress back the system, and indeed the system entropy increase represents the total entropy generation ($S_G=\Delta S_S>0$). Similarly, during reversible adiabatic expansion, the system internal thermal energy will be reduced and transferred in organized expansion work with no change of system entropy (isentropic process), since the reduction of disorganized internal energy and potential reduction of entropy will be compensated with equal increase of disorder and entropy in the expanded volume. The process could be reversed back-and-fort (like elastic compression-expansion oscillations of a system) without energy degradation and entropy change (isentropic processes). In reversible processes energy is exchanged at minimum-needed, not higher than needed potential, and isolated systems do not undergo any energy-potential related degradation/disorganization, and with total conservation of entropy.

3. HEAT TRANSFER AND IRREVERSIBILITY:
Entropy Transfer and Generation

On Figure 2a,b&c, different cases of heat transfer processes are presented to heat the same system from state 1S to 2S, using the same amount of thermal energy from three different resources (R). First case (a) uses a higher-level than necessary, constant-temperature resource, so that entropy generation, $S_G=\Delta S_S-\Delta S_R>0$, will represent irreversibility due to energy disorganization (degradation) from the higher than necessary potential (temperature). For the other two cases (b & c) multiple heat reservoirs and variable temperature heat reservoir, with minimum-necessary energy levels are used respectively, thus, in limit, without energy disorganization. The entropy reduction in the two reservoirs will be, in limit, the same as entropy increase of the system, so there will be no over-all entropy generation and the processes are reversible. The latter case, Fig. 2c, may represent an ideal counterflow heat exchanger where one system (Reservoir) is cooled from state 1R to 2R, while heating another system, with identical

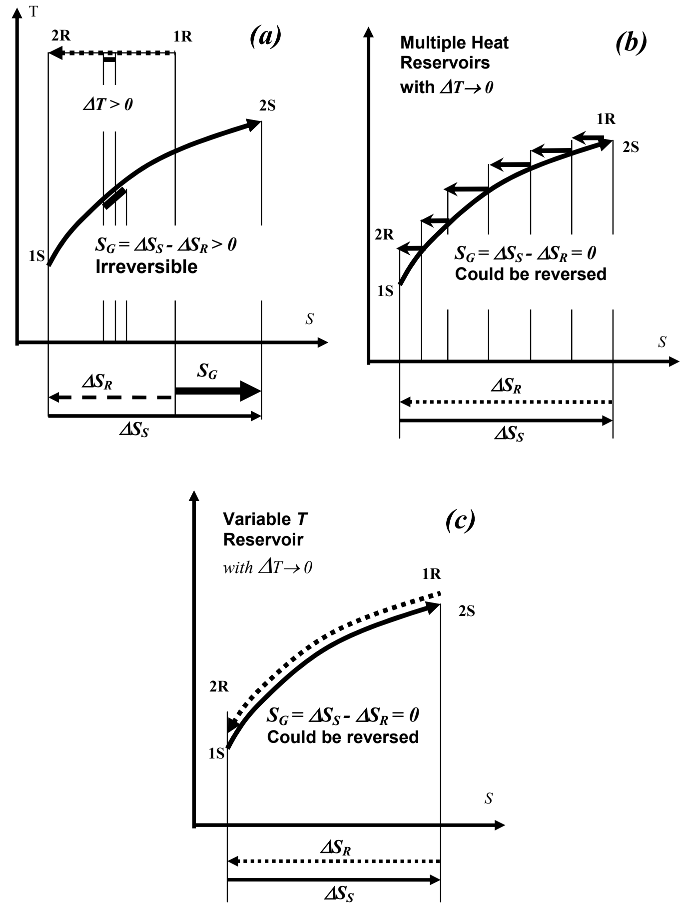

FIGURE 2: Heat transfer, entropy change and entropy generation: (a) irreversible heat transfer at finite temperature differences; (b) reversible heat transfer with multiple heat resources; (c) reversible heat transfer with variable temperature heat resource.

properties, from state 1S to 2S at infinitesimal temperature differences.

We could consider a system internal thermal energy and entropy, as being accumulated from absolute zero level, by disorganization of organized or higher level energy potential with the corresponding entropy generation. Thus entropy as system property is associated with its thermal energy. Furthermore, when thermal energy is transferred as heat the associated entropy is transferred together with heat and additional entropy may be generated if that thermal energy is further degraded to lower thermal potential or if organized work transfer is disorganized into the system, thus transformed into its thermal energy. If only work is transferred into a system in a reversible process, there will be neither energy degradation nor entropy generation, and the process could be reversed. Therefore, entropy could be transferred in reversible processes along with heat transfer, and additionally generated if work or thermal energy are disorganized at the lower thermal potential during irreversible processes. Once a process completes, any generated entropy due to irreversibility becomes (permanent) system property and cannot be reversed by itself (thus, a permanent change). Therefore, a system entropy may be only decreased if thermal energy is removed (cooling, heat transfer out), but may be increased if thermal energy is increased (heating, heat transfer in) or by entropy generation due to irreversibility of any kind. Thus, entropy transfer is due to reversible heat transfer and could be ether positive or negative, while entropy generation is always positive and always due to irreversibility.

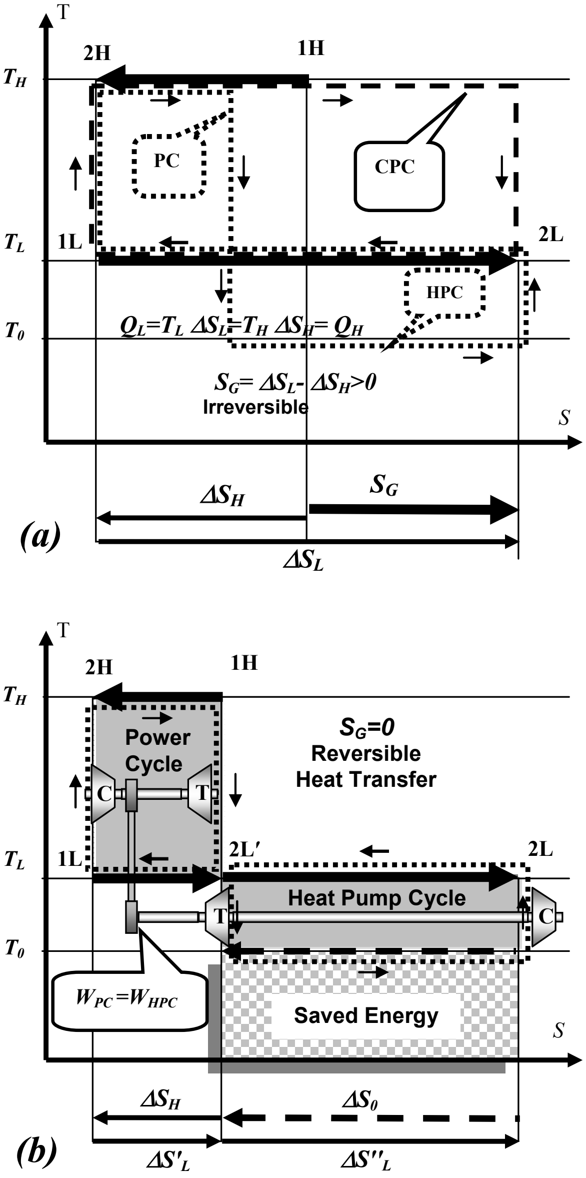

FIGURE 3: Heat transfer from a system at higher (H) to a system at lower temperature (L): (a) spontaneous irreversible heat transfer; (b) dual power-heat pump cycle reversible heat transfer.

4. REVERSIBLE HEAT TRANSFER AND PRACTICAL POTENTIALS

Heat transfer is known as typical spontaneous irreversible process with irreversible loss of energy potential (from high to low temperature; cannot be reversed) and overall entropy increase. However, since reversible (also real) adiabatic expansion and compression do change thermal-potential (temperature) without heat transfer, it makes possible, in limit, to have reversible heat transfer from one thermal potential to either lower or higher, using reversible refrigeration or combined dual, power-and-heat-pump cycles, respectively, with overall increase in efficiency. Three different cases of heating a system (L) at lower temperature, T_L, but higher than its surrounding temperature, T_0, using another system (H) at higher temperature, T_H, are presented on Fig. 3, and analyzed below. The simplest **case (1)**, most often used in practice, is presented on Fig. 3a, when thermal energy is directly transferred from higher to lower temperature ($Q_H=Q_L$) in a spontaneous and irreversible process with entropy generation, $S_G=\Delta S_L-\Delta S_H=Q_H\ /[(1/T_L)-(1/T_H)]>0$, representing the irreversibility due to energy disorganization from higher to lower potential. On the same diagram the dashed rectangle represents a possible reversible heating, **case (2)**, using a cogeneration power cycle (*CPC*) where system L will be heated by rejected cycle heat. In this reversible process, more heat $Q_H=Q_L\times(T_H/T_L)$ will be required, but in the process additional useful work, $W=Q_L\times(T_H/T_L-1)$ will be obtained, similar to the cogeneration heating in practice. The least amount of heat Q_H will be required, in **case (3),** which is the focus of this paper, if we use produced work in a reversible power cycle (*PC*) to draw additional heat from the surroundings at temperature T_0, using a reversible heat pump cycle (*HPC*), as presented by the two dotted-line rectangles on Fig. 3a, and elaborated on Fig. 3b. The net-outcome, in limit, will be "*the reversible heat transfer*" only, from high-temperature system (H) to low-temperature system (L) without any net-work produced or utilized, thus achieving the highest efficiency possible (without any energy degradation and without any entropy generation) for the given conditions, see below.

Therefore, the most efficient reversible heat transfer from system H at higher temperature T_H, to system L at lower temperature T_L, as presented on Fig. 3b, may be obtained (as limiting case) by using a dual power-and-heat-pump cycle (*PHP*), which is governed by the following conditions ($W_{PC}=W_{HPC}$):

$$(T_H-T_L)\Delta S_H=(T_L-T_0)\Delta S_0 \qquad Eq.(1)$$

$$Q_H=T_H\cdot\Delta S_H \qquad Eq.(2)$$

$$Q_L=T_L\cdot\Delta S_L=T_L(\Delta S_H+\Delta S_0) \qquad Eq.(3)$$

The coefficient of performance (*COP*) of this dual power-and-heat-pump cycle, similar to *COP*s defined for refrigeration and air-conditioning reversible heat transfer processes from lower T_R to surrounding T_0 , and for heat pump reversible heat transfer from lower surrounding T_0 to higher T_H temperature, may be obtained from Eqs. (1-3) as (see also Table I):

$$COP_{PHP}=\frac{Q_L}{Q_H}=\frac{T_L}{T_H}\cdot\frac{T_H-T_0}{T_L-T_0} \qquad Eq.(4)$$

For example, if we have to heat a space at $T_L=350\ K$ using the heat source at $T_H=1050\ K$, at surroundings temperature $T_0=300\ K$, the dual, power-heat pump (*PHP*) cycle *COP* will be:

$$COP_{PHP}=\frac{Q_L}{Q_H}=\frac{T_L}{T_H}\cdot\frac{T_H-T_0}{T_L-T_0}=\frac{350}{1050}\cdot\frac{1050-300}{350-300}$$
$$=5=500\% \qquad Eq.(5)$$

TABLE I:
COEFFICIENTS OF PERFORMANCE FOR THREE TYPICAL CASES OF REVERSIBLE HEAT TRANSFER

REVERSIBLE HEAT TRANSFER TYPE	**COEFFICIENT OF PERFORMANCE** for $T_H>T_L>T_0>T_R$
Heating from higher temperature source: *Dual Power-Heat Pump Cycle (introduced here)*	$COP_{PHP}=\frac{Q_L}{Q_H}=\frac{T_L}{T_H}\cdot\frac{T_H-T_0}{T_L-T_0}$ Eq. (4)
Cooling: *Refrigeration or Air-Conditioning*	$COP_R=\frac{Q_R}{W}=\frac{T_R}{T_0-T_R}$ Eq. (6)
Heating from lower temperature source: *Heat Pump*	$COP_{HP}=\frac{Q_H}{W}=\frac{T_H}{T_H-T_0}$ Eq. (7)

The above, Eq.(4), is not the heat-pump heating using external work, but heating a system using heat only from higher temperature source, thus without any external net-work. Therefore, the "*Dual Power-Heat Pump Cycle*" may be considered as a reversible heat-transfer transformer, from-any-to-any temperature levels. The equations in Table I represent limiting cases and practical potentials for improving efficiencies of different heat transfer applications.

5. CONCLUSION

The philosophical and practical aspects of energy and entropy, including reversibility and irreversibility, as well as the concept of "*reversible heat transfer*," utilizing the "*Dual Power-Heat Pump Cycle (PHP),*" as introduced here, could be summarized as follows:

1. Energy is a fundamental concept indivisible from matter and space, and energy exchanges or transfers are associated with all processes (or changes), thus indivisible from time.
2. Energy is "the building block" and fundamental property of matter and space, thus fundamental property of existence. For a given matter (system) and space (volume) energy defines the system equilibrium state, and vice versa.
3. For a given system state (structure and phase) addition of energy will tend (spontaneously) to randomly distribute (disorganize) over the system microstructure and space it occupies, called internal thermal energy, increasing energy-potential (temperature) and/or energy-displacement (entropy), and vice versa.
4. Energy and mass are conserved within interacting systems (all of which may be considered as a combined isolated system not interacting with its surrounding systems), and energy transfer (in time) is irreversible (in one direction) from higher to lower potential only, which then results in continuous generation (increase) of energy-displacement, called entropy generation, which is fundamental measure of irreversibility, or

permanent changes, the latter also measured with the passing time.

5. Reversible energy transfer is only possible as limiting case of irreversible energy transfer at infinitesimally small energy-potential differences, thus in quasiequilibrium processes, with conservation of entropy. Since such changes are reversible, they are not permanent (could be reversed without leaving any relevant or permanent effect on the surroundings) and, along with time, irrelevant.
6. Entropy may be transferred from system to system by reversible heat transfer and also generated due to irreversibility of heat and work transfer.
7. Heat transfer, like any other energy transfer, may be achieved from any-to-any temperature level (performed in real power and refrigeration cycles), and in limit be reversible, if temperature of an intermediary cyclic substance is adjusted as needed, using isentropic compression and expansion. The reversible heat transfer limits are the most efficient and demonstrate limiting potentials for practical heat transfer processes.

Therefore, the "*Dual Power-Heat Pump Cycle*," introduced here, may be considered as a reversible heat-transfer transformer, from-any-to-any temperature levels. The simple analysis of this dual, combined cycle (Eq. 4. and Fig. 3b), to achieve *reversible heat transfer only (from higher to lower temperature system) and without any net-work produced or utilized*, along with presented emphasis (with analysis) of underlying physical phenomena, including several hypothesis, is intended contribution of this paper.

REFERENCES (*Bibliography*)

NOTE: This paper is mostly written as reflection of author's understanding (including logical hypothesis) of the related phenomena over many years [5], including recent publication [6], while the other sources [1-4] are not used as direct "References," but are listed as "Bibliography," where the well-known facts cited in this paper are presented.

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