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Closed Processes Based Heat-Work Interactions Doing Useful Work by Adding and Releasing Heat

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ABSTRACT

Experimental observations show that, among the many heat-work interactions occurring in closed process based transformations, there is one in which compression work is done, while increasing the internal energy. Although this fact seems to be a violation of the principle of conservation of energy, in reality this does not happen, so that a closed compression process is physically possible in which net work is produced by thermal contraction of a thermal working fluid. This assertion is based on observational evidence. Thus, the objective is therefore to analyze heat-work interaction modes in closed processes conducted by heat addition, heat releasing, work applied to the process, and work done by the process. Thus, this analysis focuses on the feasible thermodynamic transformations useful for the achievement of efficient thermal cycles. Therefore, thermal analysis examining the performance of mechanical work by releasing heat from the working fluid was undertaken. The proposed cycles are characterized by performing mechanical work both in the expansion phase due to heat addition, and in the compression phase due to heat releasing. The cycles achieved are characterized by operating with closed thermal processes in which both transformations with isochoric heat addition and isochoric heat extraction are associated with useful mechanical work at high performance. Results derived from a case study between 300-700 (K) with air give an efficiency of 53.39 %, approaching the Carnot Factor.

Keywords: *Closed processes, Closed processes-based cycles, compression based contraction, Cooling-based work, Heating-based work.*

INTRODUCTION

The advances made in relation to conventional thermal cycles contribute to increasing performance when based on existing facilities for efficiently using available low-grade heat; this includes the use of residual energy rejected by many industrial processes. However, a significant amount of heat rejected from industrial applications (consisting of low-grade heat) has not yet been efficiently utilised. Conventionally, this is due to the general use of thermal engines that obey the limitations imposed by the Carnot factor on some thermal cycles, such as the Carnot and Carnot family and the Ericsson and Stirling cycles (CES). The Carnot factor (CF) is a limitation of thermal efficiency for thermal engines that obey CES-based architectures. This study, however, will examine efficient heat-work interactions which are applied to thermal engines where the thermal efficiency is not constrained by CF limitations, yet nevertheless fulfil Clausius and Kelvin Planck statements.

Background on Low-Grade Heat Applications

Although the heat-working interactions are as old as the laws of nature, some useful heat-work interaction modes has not been taken into consideration to obtain greater thermal efficiency in the closed processes of the thermal cycles. Thus, among the conventional techniques applied to obtain high efficiency thermal cycles are some that are discussed below. For example, Ferreiro et al. [1–5] proposed a non-condensing mode thermal cycle, which converts heat into mechanical work undergoing only closed thermodynamic transformations. These thermal cycles are characterized by their thermal performance, which approximates the Carnot factor with adequate operating conditions.

For instance, the thermal efficiency for a high- and low-temperature reservoir of 320 and 305 K respectively is 25.4 % with hydrogen, 36.3 % with helium and 38.1 % with argon as working fluids. The authors published research results [1], demonstrating that closed processes based cycle that works with low-grade heat sources can provide high thermal efficiency. In the same way, they described in [2] an application based on ocean thermal energy, assuming a difference of 20 (K) between top and bottom cycle temperatures with helium as a working fluid, which obtained a high thermal efficiency. Another interesting application of this trilateral cycle consists of a bottoming cycle operating with the residual heat rejected from the steam condenser of a power plant, which yielded unconventional high thermal efficiencies [3]. In [4] the researchers explored a closed processes based thermal cycle to compare adiabatic and isothermal expansions processes, where the Carnot factor is approached at certain operating temperatures. In [5] they also studied ways to select a working fluid for each temperature range in order to achieve high efficiencies under isothermal expansion. The efficiencies achieved in [1–5] are comparably higher than conventional thermal cycles exploiting waste heat.

The importance of researching low-grade heat or waste heat applications is due to the amount of heat energy available at negligible cost within the range of medium and low temperatures, with the drawback that conventional thermal cycles cannot make efficient use of such heat because they are mainly based on CES (Carnot-Ericsson-Stirling) cycles, in which some cycle transformations are open processes, which contribute to decreasing performance. Therefore, Ferreiro et al. [6], proposed a thermodynamic study of regenerative Otto based cycles with zero NOx emissions operating with adiabatic and polytropic expansion, where the Carnot factor is approached. They also presented the results of a study dealing with the analysis of the energy and entropy of closed adiabatic expansion based trilateral cycles where the Carnot factor is also approached for certain operating temperatures.

In cooling based reverse Carnot cycle systems a large amount of work has therefore been carried out, including rotary desiccant air conditioning systems, and most report that the Carnot factor is approached or even surpassed [8-13]. She et al. [8], therefore proposed a new energy-efficient refrigeration system sub-cooled by liquid desiccant dehumidification and evaporation. This system is characterised by the capacity of the liquid desiccant system to produce very dry air for an indirect evaporative cooler, where results have shown that the proposed hybrid vapour compression refrigeration system achieves significantly higher COP than conventional vapour compression refrigeration systems, at the same conditions of operation. In this way, Mandegari et al. [9], performed an exergy analysis and optimization of a dehumidification desiccant wheel (DW) system. The optimal value of the parameters used demonstrates that, when exergy destruction effectiveness is selected as the objective function, the regeneration air velocity is an optimal decision variable. Similarly, Jani. et al. [10] developed an energy and exergy analysis of a solid desiccant vapour compression hybrid air conditioning system, where the rotary desiccant dehumidifier and heater are major contributors to the exergy performance of the system. They suggest the analysis provides knowledge beneficial in determining the theoretical upper limit of the system performance.

Kim et al. [11] proposed the integration of a liquid desiccant system into an evaporative cooling-assisted 100 % outdoor air system. Simulation results show that the proposed system consumes 51 % less cooling energy compared to the conventional system. Yinglin et al. [12] experimentally tested a conventional liquid desiccant-vapour compression hybrid air-conditioning and developed a corresponding mathematical model to analyse the effect of the concentrated solution branch in the SSHE (solution-solution heat exchanger) on the cooling capacity of the evaporator. The results show that the percentage of cooling capacity loss of the evaporator exceeds 10 %, with the small concentration difference of 1.5 % in the conventional air-conditioning system. Cui et al. [13] proposed a compact desiccant-evaporative heat and mass exchanger by combining the benefits of the regenerative indirect evaporative cooling and liquid desiccant dehumidification. In this instance, the model displayed clear agreement with the experimental findings with a maximum discrepancy of 8 %. Furthermore, simulation results showed that the outlet temperature of the product air was affected by the working-to-intake air flow rate ratio and the dimensionless channel length, while the outlet humidity ratio of the product air was influenced by the length of the liquid desiccant film and the dimensionless channel length.

In the thermochemical field, Van Den Einde [14] reviewed the logic of the second law that establish the kinetic energy transfer of the ideal gas Carnot cycle as a universal limit on the convertibility of heat to work in a cyclical process. The author observed that the positive excess heat of a reaction between a supercritical solvent and a solid solute enables a closed power cycle to access input heat from successive thermal reservoirs below its normal temperature, where the heat to work conversion rate of the cycle is compared to the summed work output of ideal gas Carnot cycles using the same amount of heat from the same reservoirs. The results show that the energy conversion rate of the cycle exceeds the isentropic potential of its input heat to do work. Van Den Einde [15] also investigated the potential for complete Rankine cycle exhaust heat regeneration, where the working fluid produced in a closed condensing cycle consists of a low boiling point solvent and a solid solute, where the solution reaction yields a positive excess enthalpy in the solvent's subcritical liquid range near the bottom temperature of the cycle and exhibits retrograde solubility in the solvent's supercritical fluid range near the top temperature of the cycle, which approached the Carnot factor.

Therefore, given that the objective of this research is to analyse heat-work interaction modes to establish which can be used in closed processes based thermal cycles, the next section explores the use of feasible thermal engine structures based on reciprocating single or double acting cylinders. These structures undergo closed processes-based thermal cycles that surpass the conventional performance at moderately low top temperatures, and perform work while cooling and heating a working fluid. Section 3 then describes a case study which explores the use of a feasible double acting cylinder operating with a closed process-based thermal cycle, characterised by doing work due to heating and releasing heat from a working fluid. In section 4 the results are analysed and discussed and, finally, in Section 5, conclusions regarding the significant findings are presented and discussed.

Nomenclature

Δp_{sy}	direction of pressure changes
C_P	specific heat at constant pressure (kJ/kg-K)
C_V	specific heat at constant volume (kJ/kg-K)
η_{th}	thermal efficiency (%)
(η_c)	Carnot efficiency (%)
n	polytropic exponent
γ	adiabatic exponent
p	pressure (kPa)
p_{sy}	pressure in the closed system (kPa)
p_{su}	pressure at the surroundings (kPa)
q	specific heat flow (kJ/kg)
q_i	specific heat in (kJ/kg)
q_o	specific heat out (kJ/kg)
Q	heat (kJ)
Q_i	heat in (kJ)
Q_o	heat out (kJ)
R	ideal gas constant (kJ/kg-K)
s	specific entropy (kJ/kg-K)
T	temperature (K), [K]
T_{MAX}	Top temperature (K), [K]
u	specific internal energy (kJ/kg)
v	specific volume (m^3/kg)
V	volume (m^3)
W	work (kJ)
W_i	work in (kJ
W_{iu}	useful work in (kJ)
U_F	final internal energy (kJ)
U_I	initial internal energy (kJ)
ΔE	total change in internal energy(kJ)
w	specific work (kJ/kg)
w_i	specific work in (kJ/kg)
w_{iu}	useful specific work in (kJ/kg)
w_o	specific work out (kJ/kg)
w_n	net specific work (kJ/kg)

acronyms

CF	Carnot factor, Carnot efficiency
CES	Carnot, Ericsson and Stirling cycles
da	double acting
DAC	double acting cylinder
HEX	heat exchanger
RE	realizability (Y/N)
RON	row order number
sa	single acting
ΔV	volume change
WF	working fluid

RECIPROCATING THERMAL ENGINES UNDERGOING HEAT-WORK INTERACTIONS BASED ON CLOSED PROCESSES

The first law for closed processes is based on experimental observations, therefore it cannot be proved analytically, implying there is no process in nature that violates the first law. This law states that the net amount of energy (as heat and work) transferred to or from a closed system located within the surroundings delimited by a boundary, equals the net change (increase or decrease) in the total energy of the system. Therefore, considering that,

Q = net heat transfer between system and its surroundings $\sum Q_i - \sum Q_o$, where Q_i or Q_o respectively directly contribute to increasing or decreasing the internal energy of the closed system,

W = net work done in all forms $\sum W_i - \sum W_o$, where W_i and W_o both directly contribute to increasing or decreasing the internal energy of the closed system depending on the direction of variation of the boundary (direction of the volume changes: volume increasing implies expansion and volume decreasing implies compression independently of pressure changes),

ΔE = ΔU= net change in total energy $(U_f - U_i)$ or internal energy, given that potential, kinetic and other losses are neglected the first law can be expressed as $\sum Q_i - \sum Q_o + \sum W_i - \sum W_o = \Delta E = \Delta U = U_f - U_i$, where Fig. 1 represents the conventional structure of a closed process-based thermal system delimited by a system boundary.

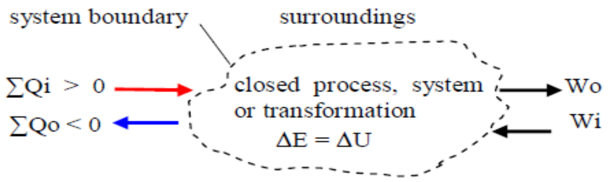

Fig1. *The conventional representation of a closed process based system to define the first principle*

In the analysis of thermal processes, as well as thermal cycles, it is customary to use specific units, commonly symbolized by lower-case letters, which denote the ratio of the value of the manipulated magnitude to the unit mass of the substance under consideration (amount of the manipulated variable per kilogram of working fluid; i.e., mechanical work can be expressed in kJ/kg). Therefore, expression (1) is written in specific magnitudes as

$$\sum q_i - \sum q_o + \sum w_i - \sum w_o = \Delta u \qquad (1)$$

A necessary and sufficient condition to obtain non-zero input or output of mechanical work in (2) is that "*the pressure difference between the system and its surroundings, as well as the system volume change, are both non-zero*".

Figure 2 depicts a closed processes-based single and double acting reciprocating engine (cylinder) as a paradigm of the feasible structure of a conventional thermal engine based on closed processes.

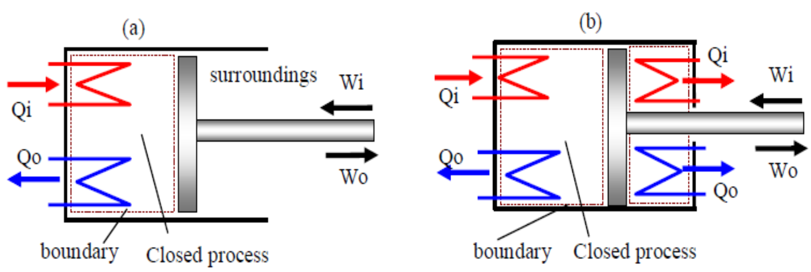

Fig2. *Closed processes based thermo-mechanical converter showing the heating and cooling heat exchangers, the piston rod used to exchange work with the closed system and its surroundings, delimited by a boundary. (a), single-acting cylinder. (b), double-acting cylinder*

As can be observed in Fig. 2, heat is added and extracted without any change of matter within the closed system. Given the first principle applied to closed processes, it follows that during an interaction of heat and work within the surroundings of a closed process, and inherently delimited by a boundary, the amount of net energy (heat or work) gained by the system must be exactly equal to the amount of net energy lost by the surroundings and vice-versa.

Nevertheless, the set of parameters taken into account in order to characterise the mechanical interactions between any closed transformation and its surroundings is related to the change in system volume (boundary changes), temperature and the pressure differences between the system and its surroundings, as well as working fluid characteristics. In such changes the internal energy, the input and output heat, as well as the input and output mechanical work, are involved.

Table1. *Convention assumed for the notation and denomination of single heat-work interaction modes with closed processes operating within a reciprocating cylinder*

process denomination	notation	ΔV	Δp_{sy}
direct compression work	w_{i_comp}	ΔV<0	$\Delta p_{sy} > 0$
suction based expansion work or (inverse expansion due to sucking or suction, contributing to decreasing the internal energy)	w_{i_suct}	ΔV>0	$\Delta p_{sy} < 0$
direct expansion work	w_{o_exp}	ΔV>0	$\Delta p_{sy} < 0$
Compression based contraction work (assumed as compression due to volume contraction causing an increase in pressure and internal energy while doing useful output work w_{iu})	$w_{iu} = w_{o\_cont}$	ΔV<0	$\Delta p_{sy} > 0$

Table 1 depicts a summary of annotated interactions. According to the equation (1) or (2) all its components (internal energy, heat and work), can interact simultaneously or independently. However, at least two of the components involved in a transformation must simultaneously interact in order to balance the equation. Ideally, it is possible to balance the equation (1) or (2) during a quasi-static compression process by cooling the system which means releasing or extracting heat from the system to the surroundings. This occurs while the boundary changes in volume (ΔV < 0) without performing mechanical work, primarily because of the infinitesimal value of the pressure difference between the system and its surroundings where inertial, friction, load forces and other effects are neglected. The fundamental heat-work interaction modes between closed systems with their surroundings can be summarised in Table 1, where it is observed that if mechanical work is performed during a closed process, a change in the internal energy or in the heat transferred followed by volume change must at least occur in order to balance the energy conservation equation and fulfil the first law.

The energy conservation balance can be established according to

- a single process balance,
- a cycle of balanced processes, as in the case of a multiple processes balance

Given the observations, closed processes-based heat-work interaction modes occur which, in the case of a cycle undergoing more than a closed transformation, obey the causality law although the law of conservation of energy must be satisfied for every closed process. That is, for a closed process the first law yields $\sum q_i - \sum q_o + \sum w_i - \sum w_o = \Delta u$. While for a closed processes-based cycle, the first law yields $\sum q_i - \sum q_o + \sum w_i - \sum w_o = 0$, which implies that $\sum q_i - \sum q_o = \sum w_o - \sum w_i$, commonly expresses as the net cycle work,

$$\sum q_i - \sum q_o = w_n \tag{2}$$

which can be assumed as the paradigm of the network because, according to the first law, it is considered to be the net cycle work

Therefore, Table 2 shows several single interaction modes dealing with the relationship between work, volume changes and associated pressure changes.

Table2. *The heat-work interaction modes between closed processes within a reciprocating cylinder and its surroundings*

p_{sy} versus p_{su}	Compression work ΔV < 0	Expansion work ΔV > 0
$p_{sy} > p_{su}$	$w_{i\_comp} > 0$	$w_{o\_exp} < 0$
$p_{sy} = p_{su}$	$w_i = w_o = 0$	$w_i = w_o = 0$
$p_{sy} < p_{su}$	$w_{o\_cont} < 0$	$w_{i\_suct} > 0$

From equation (1) it follows that $q = \sum q_i - \sum q_o$ can be less than (lt), equal (eq) or greater than (gt) zero. Furthermore, expansion and compression work are mutually exclusive interactions because, in both cases, for expansion processes the volume increases (*ΔV* gt 0), and for compression processes the volume decreases (*ΔV* lt 0), (compression and expansion cannot occur simultaneously, which means that simultaneity is neither feasible or realizable). Given the heat-work interaction modes assumed between a closed system and its surroundings, and according to the convention of signs and notation adopted in Tables 1 and 2, the energy conservation equation of equation (1) is represented in Fig 3, where w_{o_exp} and w_{o_cont} are useful mechanical works. In the case of w_{o_cont} $=w_{iu}$, the output work contributes towards increasing the internal energy, so that it is also an input work. However, in practical terms, it is a special case of useful work that provides output or useful work while simultaneously increasing the internal energy and pressure. This fact seems a controversial result, which has not been previously observed in the analysis of conventional closed processes. However this is a key to achieve useful mechanical work by releasing heat to a heat sink or surroundings.

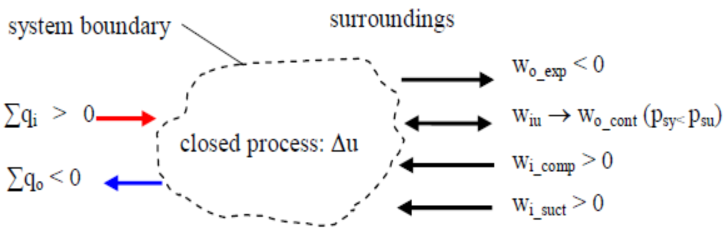

Fig3. *The proposed representation of heat-work interaction modes into the energy conservation model (first principle) for processes-based transformations*

Table 3 shows the effect of heat-work interactions on the internal energy of the closed system. It illustrates how passive mechanical work w_{i_comp}, due to direct compression and contraction work w_{o_cont}, resulting from prior cooling, contribute to increasing the internal energy, while passive mechanical work w_{i_suct} due to direct suction and expansion work w_{o_exp} contributes to decreasing the internal energy of the closed process.

Table3. *The contribution of the heat-work interactions on internal energy regardless of the direction of heat flow*

Input or passive mechanical work		Output or active mechanical work (useful work)	
w_{i_comp}	w_{i_suct}	w_{o_exp}	$w_{iu} \rightarrow w_{o\_cont}$ ($p_{sy} < p_{su}$)
$\Delta u > 0$	$\Delta u < 0$	$\Delta u < 0$	$\Delta u > 0$
$\Delta V < 0$	$\Delta V > 0$	$\Delta V > 0$	$\Delta V < 0$

According to the definitions presented in Fig. 3 and Table 3, the concept of the net specific work w_n done in all forms has changed with respect to the conventional expression given by equation (2). This is a result of adding the contraction based compression work (w_{o_cont}) to the conventional compression and expansion works.

Therefore, taking into account the implications of Tables 1-3 for heat-work interaction modes, it follows that the work defined as input work w_i is

$$\sum w_i = w_{i\_comp} + w_{i\_suct} \tag{3}$$

and the active work defined as output work w_o or useful work w_u is

$$\sum w_o = w_{o\_exp} + |w_{o\_cont}| = w_u \tag{4}$$

which, given the energy conservation equation (1) and the observational evidence suggests the energy balance can be written as

$$q + w = \sum q_i - \sum q_o + \sum w_i - \sum w_o = \sum q_i - \sum q_o + (w_{i\_comp} + w_{i\_suct}) - (w_{o\_exp} + |w_{o\_cont}|) = \Delta u \tag{5}$$

Experimental research carried out on a test rig comprising a small reciprocating double acting cylinder connected to corresponding heat exchangers suggests that, in terms of the feasible heat-work interaction modes occurring in single closed thermodynamic transformations, the energy balanced must be supported by first law as defined conventionally.

Thus, when one of the closed processes of a cycle consists of a compression based contraction process due to releasing heat from the working fluid at constant volume during a previous process of the cycle, the energy balance must take into account the fact of doing useful work by compression based contraction of the working fluid contained into the proper chamber of the cylinder.

Therefore, Table 4 show the complete solution for the energy balance based on first law, verified by means of observational evidence.

Table4. *Observed heat-work interaction modes for polytropic, isochoric, isothermal and isobaric transformations when applying the first principle (5) to a single closed transformation*

Transfer mode	ΔV	p_{sy} versus p_{su}	balance 1st law	RE	RON
Polytropic processes					
q > 0 heating	ΔV > 0 expansion	$p_{sy} > p_{su}$	$\Delta u = q - w_{o\_exp}$	Y	1
		$p_{sy} < p_{su}$	$\Delta u = q + w_{i\_suct}$	Y	2
	ΔV < 0 compression	$p_{sy} > p_{su}$	$\Delta u = q + w_{i\_comp}$	Y	3
		$p_{sy} < p_{su}$	$\Delta u = q - w_{o\_cont}$	Y	4
q = 0 adiabatic: n=γ	ΔV > 0 expansion	$p_{sy} > p_{su}$	$\Delta u = -w_{o\_exp}$	Y	5
		$p_{sy} < p_{su}$	$\Delta u = w_{i\_suct}$	Y	6
	ΔV < 0 compression	$p_{sy} > p_{su}$	$\Delta u = w_{i\_comp}$	Y	7
		$p_{sy} < p_{su}$	$\Delta u = -w_{o\_cont}$	Y	8
q < 0 cooling	ΔV > 0 expansion	$p_{sy} > p_{su}$	$\Delta u = q - w_{o\_exp}$	Y	9
		$p_{sy} < p_{su}$	$\Delta u = q + w_{i\_suct}$	Y	10
	ΔV < 0 compression	$p_{sy} > p_{su}$	$\Delta u = q + w_{i\_comp}$	Y	11
		$p_{sy} < p_{su}$	$\Delta u = q - w_{o\_cont}$	Y	12
Isochoric processes					
q > 0 heating	ΔV = 0 isochoric	$p_{sy} > p_{su}$	$\Delta u = q$	Y	13
		$p_{sy} < p_{su}$	$\Delta u = q$	Y	14
q < 0 cooling	ΔV = 0 isochoric	$p_{sy} > p_{su}$	$\Delta u = q$	Y	15
		$p_{sy} < p_{su}$	$\Delta u = q$	Y	16
Isothermal processes					
q > 0 heating	ΔV > 0 expansion	$p_{sy} > p_{su}$	$q - w_{o\_exp} = 0$	v	17
		$p_{sy} < p_{su}$	$q + w_{i\_suct} = 0$	Y	18
	ΔV < 0 compression	$p_{sy} > p_{su}$	Not applicable	**N**	19
		$p_{sy} < p_{su}$	Not applicable	**N**	20
q < 0 cooling	ΔV > 0 expansion	$p_{sy} > p_{su}$	Not applicable	**N**	21
		$p_{sy} < p_{su}$	Not applicable	**N**	22
	ΔV < 0 compression	$p_{sy} > p_{su}$	$q + w_{i\_comp} = 0$	Y	23
		$p_{sy} < p_{su}$	$q - w_{o\_cont} = 0$	Y	24
Isobaric processes					
q > 0 heating	ΔV > 0 expansion	$p_{sy} > p_{su}$	$\Delta u = q - w_{o\_exp}$	Y	25
		$p_{sy} < p_{su}$	$\Delta u = q + w_{i\_suct}$	Y	26
	ΔV < 0 compression	$p_{sy} > p_{su}$	Not applicable	**N**	27
		$p_{sy} < p_{su}$	Not applicable	**N**	28
q < 0 cooling	ΔV > 0 expansion	$p_{sy} > p_{su}$	Not applicable	**N**	29
		$p_{sy} < p_{su}$	Not applicable	**N**	30
	ΔV < 0 compression	$p_{sy} > p_{su}$	$\Delta u = q + w_{i\_comp}$	Y	31
		$p_{sy} < p_{su}$	$\Delta u = q - w_{o\_cont}$	Y	32

As a consequence of such observations, the realizable interaction modes used to convert heat to work from (5) as well as those which are not realizable, are defined and depicted in Table 4. As indicated in raw order numbers (RONs) 19-22 and 27-30, such transformations are not realizable and therefore cannot exist. Consequently, the number of feasible heat-work interaction modes is 24; among them, there is only one, the yet to be observed RON 8, which can do useful work while increasing temperature and pressure. This is due to the closed process named compression-based contraction. It is worth noting that, for a closed adiabatic transformation, neglecting some terms of the equation (5), such that

$\sum q_o = \sum q_i = \sum w_i = W_{o\_exp} = 0$, the law of conservation of energy remains as

$$-|w_{o\_cont}| = \Delta u = u_f - u_i \qquad (6)$$

which implies that, with Psy < Psu, some active work w_u (useful work) is done as output work $w_u = w_{iu} = w_{o\_cont} > 0$ due to useful work being done while increasing the internal energy during a compression based contraction process, given that

$$\Delta u + |w_{o\_cont}| = (u_f - u_i) + |w_{o\_cont}| \; > \; 0 \qquad (7)$$

Equation (7) express the amount of useful work done during an adiabatic compression process that does useful work while increasing its internal energy (compression based contraction work).

Modelling the Heat - Work Conversion Processes Based on the Generalization of the First Law

For closed processes, according to the equation (5), the first law states that

$$q + w = \Delta u = q_i - q_o + (w_{i\_comp} + w_{i\_suct}) - (w_{o\_exp} + |w_{o\_cont}|), \qquad (8)$$

The above equation states that heat interacts with closed processes as heat input q_i or heat output q_o. While input heat is transferred spontaneously when flowing from a heat source at a given temperature to working fluid at a lower temperature, heat output can leave a process being transferred to a heat sink at lower temperature.

The Case of a Thermal Process

According to references [2] and [3] useful mechanical work can be obtained from a thermal cycle by performing two sequential processes: releasing heat from a closed isochoric process followed by an adiabatic compression based contraction process that results in the cylinder volume decreasing as per RON 8 in Table 4. Thus, in the case of thermal processes, input heat is partially converted to useful mechanical work (w_{o_exp}) according to the first law as shown in Fig. 4 (a), (b) and (c), yielding

$$\Delta u = u_f - u_i = q_i - w_{o\_exp} \qquad (9)$$

However, in the case of heat output q_o, heat is partially converted to useful mechanical work ($-w_{o\_cont} = w_{iu}$) according to the first law as shown in Fig. 4 (d), (e) and (f) yielding

$$\Delta u = u_f - u_i = -q_o - w_{o\_cont} = -q_o + w_{iu} \qquad (10)$$

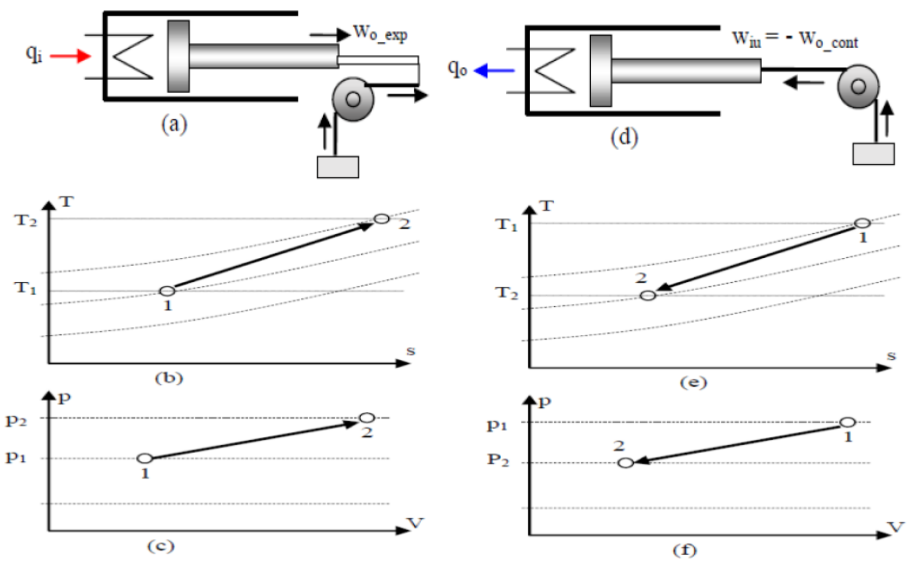

Fig4. *Heat interactions with closed processes: (a) the thermal engine doing useful expansion work w_{o_exp}; (b) the T-s diagram of the closed process doing work by heating; (c) the p-V diagram doing work by heating;(d), the thermal engine doing the useful input work (w_{iu}) required to increment the internal energy, which is equivalent to useful compression based contraction work $-w_{o\_cont} = w_{iu}$;(e), the T-s diagram of the closed process doing work by cooling; (f) the p-V diagram doing work by cooling*

The Case of a Thermal Cycle

Heat rejection occurs when an amount of input heat q_i is partially converted to useful mechanical work (w_{o_exp}) as shown in Fig. 5 (a), (b) and (c), yielding

$$\Delta u = u_f - u_i = 0, \quad q_i - q_o = w_{o\_exp} \tag{11}$$

Heat releasing or extraction by forced cooling occurs when an amount of output heat q_o is partially converted to useful mechanical work ($w_{iu} = w_{o\_cont}$) as shown in Fig. 4 (d), (e) and (f), yielding

$$\Delta u = u_f - u_i = 0, \quad q_i - q_o = -w_{o\_cont} \tag{12}$$

This means that, for thermal cycles, it follows that $q + w = 0$, which implies that for all thermal cycles

$$q + (w_{i\_comp} + w_{i\_suct}) - (w_{o\_exp} + |w_{o\_cont}|) = 0 \tag{13}$$

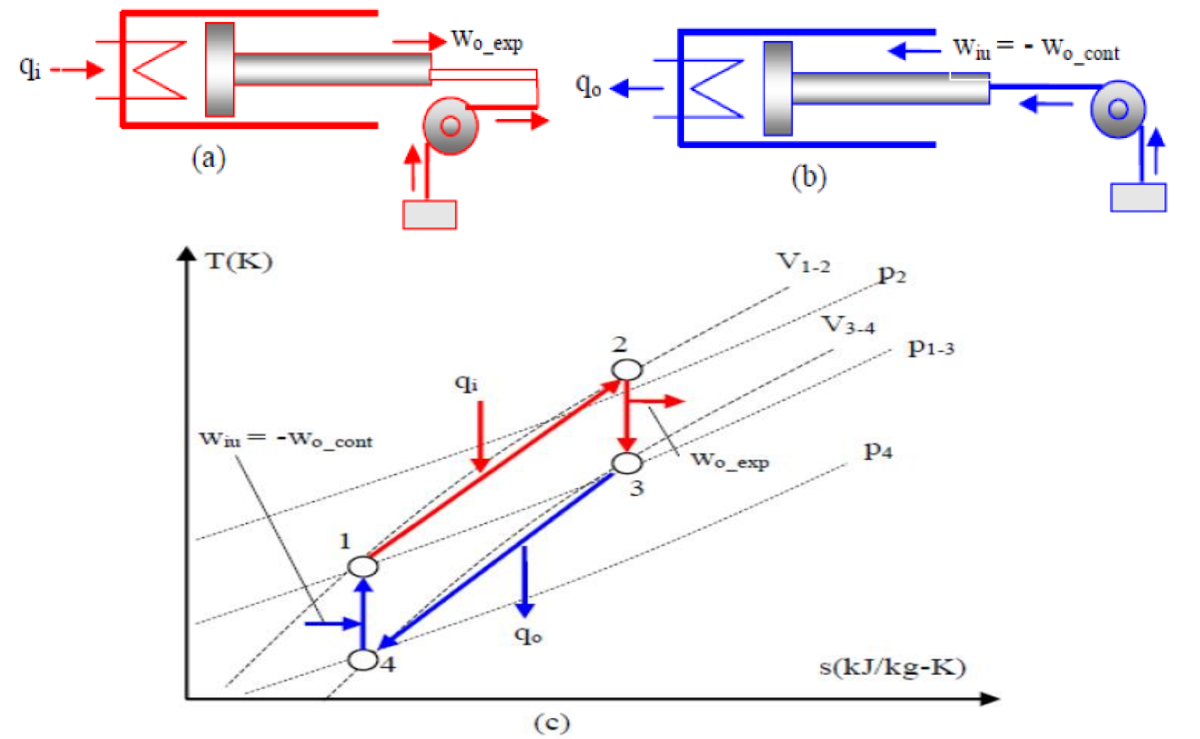

Fig5. *Heat interactions with closed processes: (a), the thermal engine doing useful direct expansion work w_{o_exp}, (b), the thermal engine doing useful compression based contraction work w_{o_cont}. (c), T-s diagram of the closed process doing work by heating and releasing heat*

Based on experimental observations, when useful work is obtained as a result of adding heat to a thermal cycle, it follows that expansion work and rejected heat is also obtained due to the heat added. This is expressed as

$$q - w_{o\_exp} = 0 \rightarrow q_i - q_o - w_{o\_exp} = 0 \tag{14}$$

As a consequence of (11), it follows that

$$q_i - q_o = w_{o\_exp} \tag{15}$$

In contrast, and also based on experimental observations, when useful work is obtained due to extracting or releasing heat only from a cycle (forced cooling, instead of rejecting heat), it follows that useful compression based contraction work w_{o_cont} (useful input work $w_{iu} = -w_{o\_cont}$)due to the contribution on increasing the internal energy of the process, although yields output useful work or compression based contraction work, denoted as w_{o_cont}) is obtained at the cost of adding heat q_i in a previous process. Applying the first principle, this is expressed as

$$q - w_{o\_cont} = 0 \rightarrow q_o - q_i - |w_{o\_cont}| = 0 \tag{16}$$

As a consequence of (16) it follows that

$$q_o - q_i = |w_{o\_cont}| \quad (17)$$

The expression (17) suggests a controversial solution as comparing (2) with (17) exposes flagrant differences between them. It therefore follows that, because (2) and (17) obey the first law, it is necessary to extend the definition of (14).

Therefore, in the case of a heating only based work thermal cycle, thermal efficiency is defined conventionally from (14) as

$$\eta_{th} = \frac{q_i - q_o}{q_i} = \frac{w_{o\_\exp}}{q_i} \quad (18)$$

However, in the case of a cooling only based work thermal cycle, the thermal efficiency is defined from (17) as

$$\eta_{th} = \frac{q_o - q_i}{q_o} = \frac{|w_{o\_cont}|}{q_o} \quad (19)$$

and the thermal efficiency of a general heating and cooling based thermal cycle as shown in case (c) of Fig. 5 is

$$\eta_{th} = \frac{w_{o\_\exp} + |w_{o\_cont}|}{q_i} \quad (20)$$

A CASE STUDY APPLIED ON A CLOSED PROCESSES-BASED THERMAL CYCLE DOING WORK BY ADDING AND RELEASING HEAT

This study is based on the achievements outlined in Section 2. It deals with the modelling task and analysis described there, according to the thermodynamic model. The study analyses a double acting cylinder that performs the thermal cycles shown in Table 6, follows the engine structure shown in Fig. 6, the p-V diagrams depicted in Fig. 7(a),7(b), and the T-s diagram in Fig. 7(c). The study was carried out for the working fluid air, assumed to be real gas in line with data provided by Lemmon et al. [16].

Table5. *Path functions associated with the quadrilateral cycle legs and for both cylinder chambers as shown in Fig. 7(d)*

Cylinder chamber A		Cylinder chamber B	
Cycle leg	Closed process based path function	Cycle leg	Closed process based path function
1–2	Isochoric (adding heat at const. vol.)	3-4	Isochoric (releasing heat at const. vol.)
2–3	Adiabatic expansion (useful work out)	4-1	Adiabatic contraction (useful work in)
3–4	Isochoric (releasing heat at const. vol.)	1-2	Isochoric (adding heat at const. vol.)
4–1	Adiabatic contraction (useful work in)	2-3	Adiabatic expansion (useful work out)

The Closed Process Based Cycle Implemented on a Double Acting Reciprocating Engine

Fig. 6 shows the structure of a reciprocating double acting cylinder as the paradigm of a thermal engine converter operated by adding and releasing heat. This thermal engine can convert the heating effect by expansion and the heat releasing effect into mechanical work, undergoing the thermal cycle depicted in Fig. 7. Every cylinder chamber is equipped with two heat exchangers (HEX): A1, A2 for chamber A and B1, B2 for chamber B. Every HEX can act as a heater or cooler under a controlled sequence, so that the heat exchanger in each chamber changes its role in order to facilitate the task of heat addition and heat releasing at constant volume.

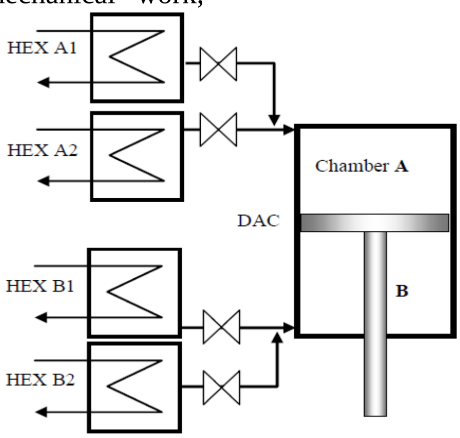

Fig6. *Depicts a closed processes-based double-acting reciprocating engine (cylinder) which does work while heating and cooling; it is an example of the feasible structure of a conventional thermal engine based on closed thermal processes*

The layout of the closed processes based thermal cycle analysed in the proposed case study is depicted within Fig. 7, where Fig. 7 (a) shows the p-V diagram in the cylinder chamber A; (b) the p-V diagram in the cylinder chamber B; (c) the T-s diagram of the cycle performing work while heating and releasing heat and (d), the simultaneous state points of the T-s and p-V diagrams for chambers A and chamber B of the double acting cylinder.

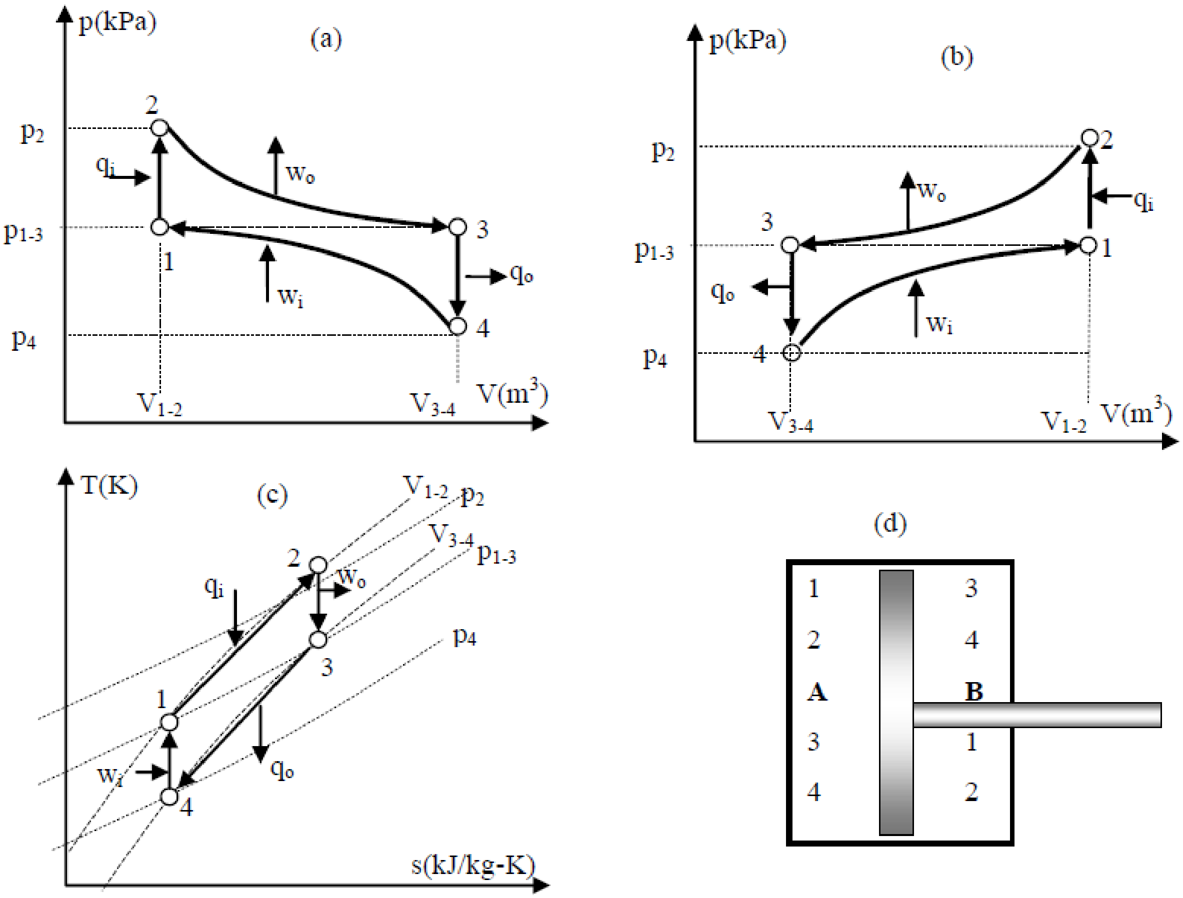

Fig7. *T-s diagrams of the proposed thermal cycles: (a) the p-V diagram of the quadrilateral cycle in the cylinder chamber A; (b) the p-V diagram of the quadrilateral cycle in the cylinder chamber B; (c), T-s diagram of the quadrilateral cycle performing work while heating and cooling; (d) the simultaneous state points of the T-s and p-V diagrams for cylinder chamber A and cylinder chamber B*

The Studied Thermal Cycle Doing Useful Work by Releasing Heat

Based on the highlighted heat-work interaction modes shown in Table 4, there is a special one which suggests the possibility of performing mechanical work as a result of releasing heat to a heat sink. This can be carried out by means of two sequential processes: an isochoric process of heat releasing and an adiabatic compression process with net mechanical work and internal energy increase based on a contraction based compression.

The proposed thermal cycle in which heat-work interactions are based on heat release is composed by two isochoric transformations (heating and cooling), and two adiabatic transformations (doing work by added heat, and doing work by extracting heat). The closed process performed within the cycle is summarised as follows:

Leg 1-2: Corresponds to a closed isochoric heating process. The amount of heat added from an external heat source at constant volume is

$$w_{12} = 0, \quad q_{12} = u_2 - u_1 = Cv \cdot (T_2 - T_1) \tag{21}$$

Leg 2-3: Corresponds to a closed adiabatic process. Thus, because there is no heat transfer from an external source, the change in internal energy is completely converted into mechanical work according to the general expression

$$q_{23} = 0, \quad u_2 - u_3 = w_{23} = \frac{p_2 \cdot v_2 - p_3 \cdot v_3}{\gamma - 1} = Cv \cdot (T_2 - T_3) \tag{22}$$

Leg 3-4: Corresponds to a closed isochoric cooling process. The amount of heat extracted to a heat sink at constant volume is

$$w_{34} = 0, \quad q_{34} = u_3 - u_4 = Cv \cdot (T_3 - T_4) \tag{23}$$

Table6. *The path functions (closed processes) assigned to each leg of the T-s diagrams of the proposed cycles depicted in Figs. 5, 6 and 7*

Closed processes			
legs	process	first law: $q + (w_{i\_comp} + w_{i\_suct}) - (w_{o\_exp} + \lvert w_{o\_cont} \rvert) = \Delta u = 0$	entropy changes
1-2	isochoric	$w_{1-2} = 0,\ q_i = q_{1-2} = \Delta u_{1-2} = Cv \cdot (T_2 - T_1)$	$S_2 > S_1$
2-3	adiabatic	$q_{2-3} = 0,\ w_{o\_exp} < 0;\ w_{o\_exp} = Cv \cdot (T_2 - T_3)$	$S_2 = S_3$
3-4	isochoric	$w_{3-4} = 0,\ q_o = q_{3-4} = \Delta u_{3-4} = Cv \cdot (T_3 - T_4)$	$S_4 < S_3$
4-1	adiabatic	$q_{4-1} = 0,\ w_{o\_cont} < 0;\ w_{i\_cont} = Cv \cdot (T_1 - T_4)$	$S_4 = S_1$
Cycle			
1-2-3-4-1		$w_U = w_{o\_exp} + \lvert w_{o\_cont} \rvert = Cv \cdot (T_2 - T_3) + Cv \cdot (T_1 - T_4)$ $\eta_{th} = \frac{w_u}{q_{2-1}} = \frac{Cv \cdot (T_2 - T_3 + T_1 - T_4)}{Cv \cdot (T_2 - T_1)}$	$\Delta s = 0$

Leg 4-1: Corresponds to a closed adiabatic process. Consequently, because there is no heat transfer between the process and its surroundings, the change in internal energy is fully converted into mechanical work according to the general expression

$$q_{41} = 0, \quad u_1 - u_4 = w_{14} = \frac{p_4 \cdot v_4 - p_1 \cdot v_1}{\gamma - 1} = Cv \cdot (T_1 - T_4) \tag{24}$$

Table 6 presents a summary of the mathematical model of the proposed cycle, which operates by adding and releasing heat and is depicted in Figs. 5, 6 and 7.

The Cycle Data of the Case Study

The case study considers air as real working fluids. The data for each cycle point is taken from [16].

In the case of air as a working fluid, converting heat to work by adding heat, the cycle points associated with the cycle parameters are shown in Table 7 and Fig. 8, which shows the T-s diagram. In the case of air as a working fluid, converting heat to work by releasing heat, the cycle points associated with the cycle parameters are shown in Table 8 and Fig. 9, which shows the T-s diagram.

In the case of air as a working fluid, converting heat to work by both adding and releasing heat, the cycle points associated with the cycle parameters are shown in Table 9, and Fig. 10, which shows the parameters of the quadrilateral cycle operating by adding and releasing heat in single acting mode. In this case, the engine structure is depicted in Fig. 7.

Table7. *Cycle parameters of the trilateral cycle operating by adding heat only with air*

point	T_i	p_i	v_i	s_i	u_i
	K	kPa	m^3/kg	kJ/kg·K	kJ/kg
1	300.0	100.00	0.8611	5.706	214.3
2	700.0	233.30	0.8611	6.333	512.7
3	556.1	100.00	1.596	6.333	401.8

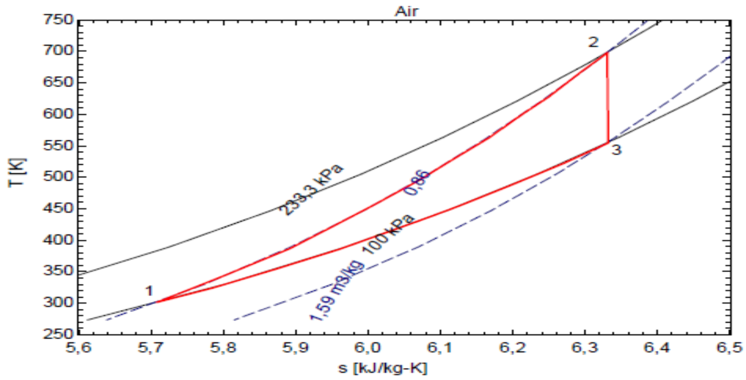

Fig8. *The trilateral cycle with added heat only*

Table8. *Cycle parameters of the trilateral cycle operating by releasing heat only*

point	T_i	p_i	v_i	s_i	u_i
	K	kPa	m^3/kg	kJ/kg·K	kJ/kg
1	381.9	100.00	1.096	5.949	273.3
3	700.0	100.00	2.009	6.576	512.7
4	300.0	42.86	2.009	5.949	214.3

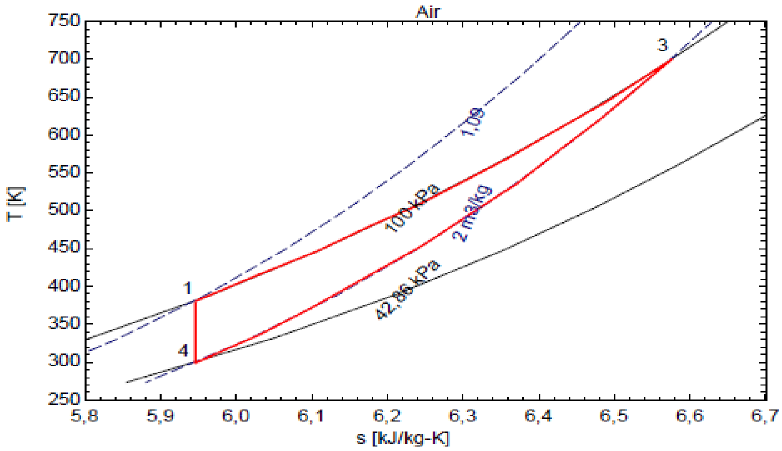

Fig9. *The trilateral cycle with releasing heat only*

Table9. *Cycle parameters of the quadrilateral cycle operating by heating and releasing heat in singe acting mode*

point	T_i	p_i	v_i	s_i	u_i
	K	kPa	m^3/kg	kJ/kg·K	kJ/kg
1	360.9	100.00	1.036	5.896	258.1
2	700.0	194.00	1.036	6.386	512.7
3	581.9	100.00	1.670	6.386	421.3
4	300.0	51.55	1.670	5.896	214.3

Table10. *Cycle parameters of the quadrilateral cycle operating by heating and releasing heat in double acting mode*

point	T_{Ai}	p_{Ai}	v_{Ai}	s_{Ai}	u_{Ai}	T_{AB}	p_{Bi}	v_{Bi}	s_{Bi}	u_{Bi}
	K	kPa	m^3/kg	kJ/kg·K	kJ/kg	K	kPa	m^3/kg	kJ/kg·K	kJ/kg
1	360.9	100.00	1.036	5.896	258.1	581.9	100.00	1.670	6.386	421.3
2	700.0	194.00	1.036	6.386	512.7	300.0	51.55	1.670	5.896	214.3
3	581.9	100.00	1.670	6.386	421.3	360.9	100.00	1.036	5.896	258.1
4	300.0	51.55	1.670	5.896	214.3	700.0	194.00	1.036	6.386	512.7

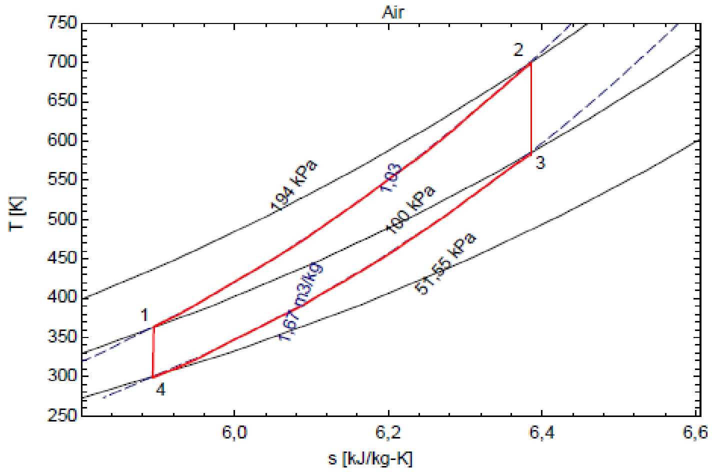

Fig10. T-*s diagram of the parameters of the quadrilateral cycle operating by heating and releasing heat in singe acting mode*

ANALYSIS OF RESULTS AND DISCUSSION

In section 2, based on experimental observations, a complete set of closed processes based heat-work interaction modes were depicted. Among the possible 24 heat-work interaction modes, a special one has been found: the previously unobserved RON 8.

Therefore, in Table 4 it can be said that the energy balance of a closed process depicted in RON 8 (compression based contraction work), is characterized by performing useful mechanical work while increasing pressure and internal energy, which means that an input work behavior (which increases the internal energy) is in practical terms identical to an output useful work.

Such an extraordinary phenomenon has never been observed before, and has severe implications for the energy balance of closed processes based cycles conducted by heat addition and heat releasing according to observational evidence. Fortunately, such consequences imply a significant advantage, thanks to the effect of releasing heat (useful work by a compression based contraction process), as the thermal efficiency is significantly increased. As shown before, the general expression of the first law (energy balance) applied on closed processes based cycles has been extended according to equations (5), (6) and (8) to reflect this phenomenon.

It is observed also that "*If no closed process of the cycle does not violate the first law, then the energy balance of the cycle does not violate the first law either*".

However, among the possible 24 heat-work interaction modes, only one, the RON 8, present such particular characteristic: *an adiabatic closed process in which useful work is done while increasing the internal energy.*

Discussion of Results

Drawing on equations (9) to (17), and based on the first principle in line with equation (8), the results of the cycle analysis are depicted in Table 11, where results for a heating only cycle, a cooling only cycle, a single acting heating and cooling cycle, and a double acting heating and cooling cycle are shown. The input-output heat, the work due to adding and releasing heat, as well as the thermal efficiencies, are also shown.

It is worth noting the thermal efficiencies of the proposed cycles. In all cases, it is significant. However, cycles that use the heating and cooling effect such as the one represented in the bottom row of Table 11 (a double acting heat in-out) exhibit an exceptional performance: High specific work and high thermal efficiency.

Table11. *Input-output heat, work due to adding and releasing heat, and the thermal efficiencies for air as working fluid; nominal pressure 100 kPa; bottom and top temperatures 300-700 K*

Heat flow	q_i	q_o	w_o	$\lvert w_i\rvert = w_{iu}$	$\Sigma\lvert w\rvert = w_n$	η_{th}
	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	%
Heat in only	298.40	187.50	110.90	0.00	110.90	37.16
Heat out only	240.80	298.40	0.00	57.60	57.60	23.93
heat in-out (se)	254.50	207.00	91.34	43.81	135.20	53.51
heat in-out (de)	506.30	414.00	182.70	87.62	270.30	53.39

Table 12 presents the performance of the proposed cycles for air as working fluid. It is observed that the works due to heating and cooling are consistent with the amount of heat transferred to and from the cycle. However, while specific work exhibits a certain dependence on the specific heat of every working fluid, the thermal efficiency does not.

In fact, the specific work is proportional to the heat energy potential or temperature.

The useful work depicted in Table 5 is computed in line with equation (8), for which $\Sigma w = w_n = w_o + \lvert w_i\rvert$. The thermal efficiency is computed taking into account that, in all cases, the released heat q_o is extracted without any calculable cost.

Table12. *Main results for the quadrilateral cycle, operating by heating and releasing heat in double acting mode with air, operating between temperatures 300 - 700 K*

WF	q_i	q_o	w_o	$\lvert w_i\rvert = w_{iu}$	$\Sigma\lvert w\rvert = w_n$	η_{th}
	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	%
Air	506.30	414.00	182.70	87.62	270.30	53.39

Conclusions

In this paper, the heat-work interaction modes carried out in closed processes conducted by heat addition and heat releasing were analyzed.

This analysis was inspired by the results of previous experiments, which found that, among the possible 24 heat-work interaction modes that occur in single closed process based transformations, there is one in which useful compression based contraction work is done while increasing the internal energy adiabatically. The consequences of this assertion based on observational evidence implies advantageous dramatic changes of the concept of performing useful mechanical work.

The analysis was performed on a double-acting cylinder operating according to a closed processes-based thermal cycle with air and hydrogen as the working fluids. The proposed and analyzed thermal cycle operates in such a way that it performs mechanical work by direct expansion due to heat addition, and by compression (compression-based contraction) due to heat releasing. The performance observed in the case study operating between 300-700 (K) with air an efficiency of 53.99 %, while the specific work amounts were 270.3 (kJ/kg). This largely surpasses the thermal efficiency of conventional thermal cycles operating bay adding heat only.

Given that the proposed cycles based on doing work by releasing heat are suitable for operating at high thermal efficiency even at low temperatures, and that the cooling is absolutely cost-effective (i.e. at no cost), and that most low-grade heat as well as waste heat costs are not significant, the widespread use of such technologies is anticipated.

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