# Efficient thermal cycle undergoing adiabatic contraction based work by releasing heat

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## ABSTRACT

By means of observational evidence it is shown that, among the vast amount of heat-work interactions occurring in closed process based transformations, there exists the possibility of doing a transformation characterized by doing useful mechanical work by contraction based compression, while increasing the internal energy. Such thermodynamic transformation has never been considered in processes. However, in reality closed contraction based compression process are physically possible in which net work is produced by contraction of a thermal working fluid while fulfilling the fundamental laws. Thus, the objective is therefore to analyze heat-work interaction modes in closed processes conducted by heat addition, heat extracting and net work done by the process. Therefore, this analysis focuses on the feasible thermodynamic transformations contributing to the achievement of efficient closed processes based thermal cycles. 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. The analysis of the cycle between top working temperatures ranging from 350 to 700 K while botom temperature approaches 300 K has been carried out, corroborated by experimental validation for low temperatures, in the order of 350 degrees Kelvin through a test bench designed specifically for this task. It is also worth noting that the thermal efficiency is independent of the temperature ratio. Therefore the results indicate that for lower temperatures below 690 K, the thermal efficiency of the cycle exceeds the Carnot factor, which is an efficient means of recovering residual or low-grade heat efficiently.

*Keywords: Closed processes, Closed processes-based cycles, Contraction work, Cooling-based work Expansion work, Heat-work interaction, Heating-based work.*

| ***Nomenclature*** | |
|---|---|
| $\Delta p_{sy}$ | direction of pressure changes |
| $C_P$ | specific heat at constant pressure (kJ/kg-K) |
| $C_V$ | specific heat at constant volume (kJ/kg-K) |
| $\eta_{th}$ | thermal efficiency (%) |
| $(\eta_c)$ | Carnot efficiency (%) |
| $n$ | polytropic exponent |
| $\gamma$ | 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) |

| ***acronyms*** | |
|---|---|
| *CF* | Carnot factor, Carnot efficiency |
| *CES* | Carnot, Ericsson and Stirling cycles |
| *COP* | coefficient of performance |
| *HEX* | heat exchanger |
| *psm* | piston stroke motion |
| $p_{sy}$ | system pressure |
| $p_{su}$ | surrounding pressure |
| $\Delta V$ | volume change |
| *WF* | working fluid |

| | |
|---|---|
| $q_i$ | 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 ($m^3$) |
| $w$ | specific work (kJ) |
| $w_i$ | specific work in (kJ) |
| $w_{i(comp)}$ | specific compression work in (kJ) |
| $w_{i(suct)}$ | specific suction work in (kJ) |
| $w_o$ | specific work out (kJ/kg) |
| $w_{o(exp)}$ | specific expansion work out (kJ/kg) |
| $w_{o(cont)}$ | specific contraction work out (kJ/kg) |
| $w_n$ | net specific work (kJ/kg) |

## 1. INTRODUCTION

The contributions on the field of heat recovery technologies carried out recently has a positive impact in relation to conventional thermal cycles, contributing to increasing performance when based on existing facilities for efficiently using available low-grade heat; this includes the use of wasted or residual heat energy exhausted by many thermal processes. Nevertheless, a significant amount of heat rejected from industrial applications (mainly low-grade heat) has not yet been efficiently utilised. Conventionally, this is due to the general use of thermal engines that obey the Carnot, Ericsson or Stirling (*CES*) constraints. The Carnot factor (*CF*) is an efficiency limitation for thermal engines that obey *CES*-based architectures, which undergoes two temperature levels. Due to such constraints, this study will analyse efficient heat-work interaction modes to be applied to thermal engines where the thermal efficiency is not constrained by *CF* limitations, yet nevertheless fulfil Clausius and Kelvin Planck statements. 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 thermo-chemical 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.

Based on the state of the art technologies, it has been observed that some useful heat-work interaction modes has not been taken into consideration to obtain greater thermal efficiency thermal cycles that undergoes closed processes without phase changes. 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.

## 2. SINGLE CLOSED PROCESSES BASED HEAT WORK INTERACTIONS

Discarding potential and kinetic energies, the displacement based mechanical work can only be done by means of two heat-work interaction modes undergoing any thermodynamic system:

-- by a thermodynamic transformation due to the addition of heat to the thermal working fluid, and/or

-- by a thermodynamic transformation due to the extraction of heat from the thermal working fluid.

Generally the heat can be added at constant volume or at variable volume. In this study the addition and extraction of heat will be considered as an isochoric process. As shown in Fig 1(a) Fig. 1(b), this characteristic does not imply that the piston remains motionless during the addition and extraction of heat, because during the addition and extraction of heat to/from the working fluid, the volume of the cylinder remains isolated from the heat transfer enclosures by means of its respective valve, which allows his movement freely, while the enclosures volume remain constant.

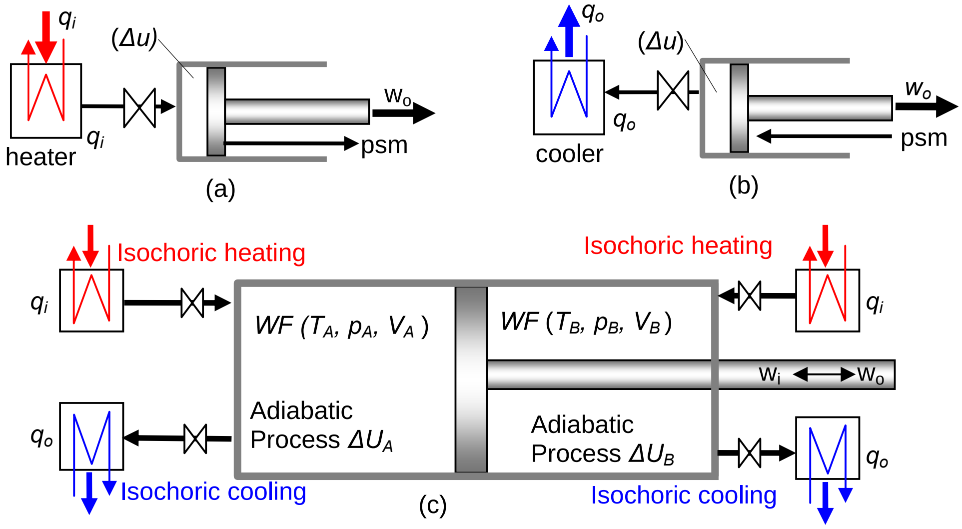


Fig. 1. Single and double-acting cylinder showing the basic heat work interaction modes by adding and extracting heat associated to the psm (piston stroke motion). (a), single-acting cylinder delivering useful work by expansion due to adding heat at constant volume to a working fluid during a previous heating process. (b), single-acting cylinder delivering useful work by contraction (contraction based compression) due to releasing heat at constant volume from a working fluid during a previous cooling process. (c), double-acting cylinder chterised by performinf simultaneously the tasks described in (a) and (b).

Discarding the effect s of kinetic and potential energies, in closed processes based transformations the first law indicates us the behaviour of the heat work interaction modes according to

$$\sum q+\sum w=\Delta u \qquad (1)$$

The same expression detailing the input-output energy of represented in (2) as

$$\sum q_i - \sum q_o + \sum w_i - \sum w_o = \Delta u \qquad (2)$$

where Fig. 1 (a) and (b) depicts two heat-work interaction modes which undergoes delivering of useful mechanical work by means of adding or releasing heat from a working fluid undergoing closed processes based thermodynamic transformations.

With reference to the heat-work interactions depicted by Fig. 1(a), follows that adding heat to the working fluid contained in the cylinder chamber, and extracting useful mechanical work ($w_{o(exp)}$ by expansion of the working fluid undergoing the displacement of the piston from the left to the right side, internal energy will be described by (2), as.

$$\sum q_i - \sum w_{o(\exp)} = \Delta u \text{ or,} \qquad (3)$$

$$q_i = w_{o(\exp)} + \Delta u \qquad (4)$$

Eq. (2) satisfies the principle of the conservation of energy and consequently the first law of the thermodynamics.

Since expression (2) and consequently expression (4) is a general expression, then when applied to the case of Fig. 1(b), follows that releasing heat from the working fluid contained in the cylinder chamber, and extracting useful mechanical work ($w_{o(cont)}$) by contraction of the working fluid undergoing the displacement of the piston from the right to the left side, internal energy will be described by Eq. (2) as

$$-\sum q_o - \sum w_{o(cont)} = \Delta u \text{ or,} \qquad (5)$$

$$-q_o = w_{o(cont)} + \Delta u \text{, or} \qquad (6)$$

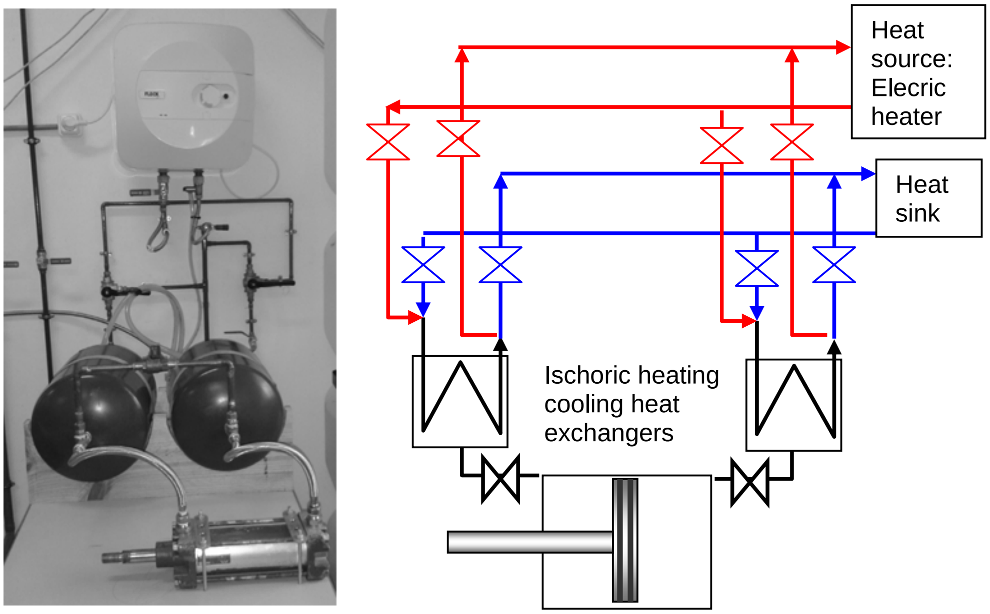
$$q_o = -(w_{o(cont)} + \Delta u) \qquad (7)$$

Eq. (7) based on the first law confirms that the extracted heat undergoing a closed transformation produces useful net work by contraction based compression of the working fluid. Thus, the heat-work interaction modes described by means of the Eqs. (4) and (7) are rigorously true according to the principle of conservation of energy and, consequently, the first law of thermodynamics. They cannot be refuted since they are backed by theoretical and observational evidence. Equation (7) expresses the amount of useful work done during an adiabatic compression process that does useful work while increasing its internal energy (compression based contraction work).

### 2.1. The experimental set up implemented on a test rig consisting of a double effect reciprocating cylinder.

Fig.2. depicts the test rig composed by a double effect reciprocation cylinder equipped with heat transfer fluid piping, control valves and heat exchangers. 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. The working fluid used in the heat-work interactions carried out is air. In the experiments carried out according to the results of Table 1, it is interesting to

know the qualitative behaviour of the closed processes subjected to addition and extraction of heat, rather than the quantitative behaviour.



(a) (b)

Fig. 2. Test rig to verify single heat-work interaction modes designed to carry out basic experimental proofs of concept based on patent publication number 2 680 043 and application priority number 201700181. It is equipped with heat exchangers, heating and cooling heat transfer fluids, piping, control valves, and a reciprocating double acting cylinder. (a), the aspect of the test rig. (b), the schematic layout of the test rig.

Based on the structure depicted in Fog. 2, the characteristics of the basic test rig are: Heat transfer fluids for heat source and heat sink, water. Thermal working fluid for concept proof, standard air. Range of heat transfer flow, 0.0-002 $m^3$/min. Working fluid pressures for proof of concept, 50-150 kPa. Temperature for the basic proof of concept 300-400 K. Double acting cylinder, A84B2 pneumatic cylinder 82,5 mm bore and 101.6 mm stroke.

As indicated in the Table 1, closed isochoric heat-work interaction modes cannot do useful work, so that among the possible processes exhibiting the ability to do mechanical work there are only those in which volume changes. Therefore,

- as consequence of adding heat at constant volume to a working fluid it is possible a subsequent expansion process which undergoes useful mechanical work, as shown in Fig. 1 (a)
- as consequence of extracting heat at constant volume from a working fluid it is possible a subsequent contraction process which undergoes useful mechanical work as shown in Fig. 1 (b).

Table 1. Observed heat-work interaction modes for closed processes based, isochoric, and adiabatic transformations when applying the first principle to a single closed transformation

| **Transfer mode** | **$\Delta$V** | **$p_{sy}$ versus $p_{su}$** | **$1^{st}$ law balance** |
|---|---|---|---|
| | | **Isochoric processes** | |
| $q > 0$<br>heating | $\Delta V = 0$<br>isochoric | $p_{sy} > p_{su}$ | $\Delta u = q = q_i$ |
| | | $p_{sy} < p_{su}$ | $\Delta u = q = q_i$ |
| $q < 0$<br>cooling | $\Delta V = 0$<br>isochoric | $p_{sy} > p_{su}$ | $-\Delta u = -q = q_o$ |
| | | $p_{sy} < p_{su}$ | $-\Delta u = -q = q_o$ |
| | | **Adiabatic processes** | |
| $q = 0$ | $\Delta V > 0$<br>expansion | $p_{sy} > p_{su}$ | $\Delta u = -w_{o(\exp)}$ |
| | | $p_{sy} < p_{su}$ | $\Delta u = w_{i(suct)}$ |
| | $\Delta V < 0$<br>compression | $p_{sy} > p_{su}$ | $\Delta u = w_{i(comp)}$ |
| | | $p_{sy} < p_{su}$ | $\Delta u = -w_{o(cont)}$ |

As a consequence of such observations, some feasible heat-work interaction modes used to convert heat to work are defined and depicted in Table 1. Therefore, Table 1 show the complete solution for the energy balance based on first law in the case of closed processes based adiabatic expansion and contraction as a real means of doing useful mechanical work, verified by means of experimental evidence.

The heat work interaction modes described in Table 1 have been verified by means of the test rig depicted in Fig 2. Every heat exchanger is equipped with piping and control valves so that it can operate as cooler or heater according the role assigned by means of a circular timing diagram not represented in this section.

Obviously most of the heat-work interaction modes are very common, so that no test is necessary to comprehend its behaviour. However there are some of them as indicated above that needs an experimental proof to validate its behaviour, such for instance the case of those observed in Table 1.

### 2.2. Energy balance of a closed process based thermal cycle that does useful work by extracting heat

Considering both described heat-work interaction modes shown in (4) and (7) into a thermal cycle described in Fig. 4, it is necessary taking into consideration the fact that internal energy cannot change in a completed cycle.

Therefore Eq. (2) with regard to the first principle can be written as

$$\sum q_i - \sum q_o + \sum w_i - \sum w_o = \Delta u \,, \qquad (8)$$

Furthermore, considering that for every completed cycle the internal energy remains constant, its change is zero.

$$\Delta u = 0$$

In addition, admitting that there are no work interactions entering any process of this particular thermal cycle, it happens that:

$$\sum w_i = 0$$

Consequently, Eq. (8) can be expressed accurately as

$$\sum q_i - \sum q_o = \sum w_o \tag{9}$$

Therefore, when one of the closed processes of a cycle consists of a contraction process due to extracting 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 contraction based compression of the working fluid contained into the proper cylinder chamber. Thus, the net work $w_n$ of a cycle that operates undergoing the transformations given by (4) and (7) can be assumed as

$$w_n = w_{o(\exp)} + w_{o(cont)} \tag{10}$$

The heat balances expressed along Eqs. (1-9) are correct and fulfil the first law. Nevertheless, it will be shown that while single closed transformation based heat-work interaction modes cannot be refuted such as (4) and (7), obeying rigorously the first law, when dealing with thermal cycles which delivers useful work by extracting heat, Eq. 9 is not useful. Such controversial result has been experimentally proved by means of a test rig based on a double-acting cylinder equipped with heat transfer exchangers for adding and extracting heat as shown in Fig. 2, and the results depicted in Table 1.

Based on the observed experimental results expression (10) described the net work along the cycle where the difference between added and extracted heat tends toward a quantity (difference between added heat $q_i$ and extracted heat $q_o$ to/from a cycle as a real number $q_R$) according to the expression

$$(q_i - q_o) \to q_R \tag{11}$$

such that

$q_R < w_n$, or

$$q_R < (w_{o(\exp)} + w_{o(cont)}) \tag{12}$$

while satisfying the condition $q_i - q_o > 0$ into the range of operating conditions. Since the cost of extracting heat from the working fluid (cooling process) is assumed as negligible, then the only cost attributable to the cycle is due to the addition of heat. Therefore, the thermal efficiency of a general heating and cooling based thermal cycle as shown by (10), is

$$\eta_{th} = \frac{w_o}{q_i} = \frac{w_n}{q_i} = \frac{w_{o(\exp)} + w_{o(cont)}}{q_i} \tag{13}$$

### 2.3. Modelling the studied thermal cycle doing useful work by heating and 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

$$w_{12} = 0, \quad q_{12} = u_2 - u_1 = Cv \cdot (T_2 - T_1) \tag{14}$$

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

$$q_{23} = 0, \quad u_2 - u_3 = w_{23} = \frac{p_2 \cdot v_2 - p_{3.} \cdot v_3}{\gamma - 1} = Cv \cdot (T_2 - T_3) \tag{15}$$

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

$$w_{34} = 0, \quad q_{34} = u_3 - u_4 = Cv \cdot (T_3 - T_4) \tag{18}$$

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

$$q_{41} = 0, \quad u_1 - u_4 = w_{14} = \frac{p_4 \cdot v_4 - p_{1.} \cdot v_1}{\gamma - 1} = Cv \cdot (T_1 - T_4) \tag{16}$$

Table 4 presents a summary of the mathematical model of the proposed cycle, which operates by adding and releasing heat.

Table 4. The path functions (closed processes) assigned to each leg of the T-s diagrams of the proposed cycle depicted in Fig. 4

| 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 | | $w_U = w_{o\_exp} + \lvert w_{o\_cont} \rvert = Cv \cdot (T_2 - T_3) + Cv \cdot (T_1 - T_4)$<br>$\eta_{th} = \frac{w_u}{q_{2-1}} = \frac{Cv \cdot (T_2 - T_3 + T_1 - T_4)}{Cv \cdot (T_2 - T_1)}$ | $\Delta s = 0$ |

## 3. A CASE STUDY UNDERGOING CONTRACTION BASED COMPRESSION WORK

In this section, a case study applied on a closed processes-based thermal cycle characterised by doing work by adding and releasing heat, which undergoes useful contraction work, is described and analysed.

In Fig. 3, it is shown the structure of a reciprocating double acting cylinder as the paradigm of a thermal engine converter operated by adding and releasing heat, which has the ability to do useful work, by contraction of the working fluid. This thermal engine can convert the isochoric heating effect by expansion of the working fluid and the heat releasing effect by contraction of the working fluid into useful mechanical work, which obeys the thermal cycle depicted in Fig. 4, represented by both *T-s* and *p-V* diagrams. Every cylinder chamber is equipped with two heat exchangers (HEX): heater HEX 20 and cooler HEX 30 to add and release heat to/from cylinder chamber A, and heater HEX 21 and cooler HEX 31 to add and release heat to/from cylinder chamber B.

Furthermore, in Fig. 3 it is shown that both, the heaters and coolers transfer heat by forced convection. The forced convection for transferring heat between the heat transfer fluid and the thermal working fluid is obtained by means of circulating fans. A feed compressor for each cylinder chamber is also necessary to transfer the cool working fluid to the heater heat exchangers.

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 was carried out for the working fluid air, assumed to be real gas in line with data provided by Lemmon et al. [16].

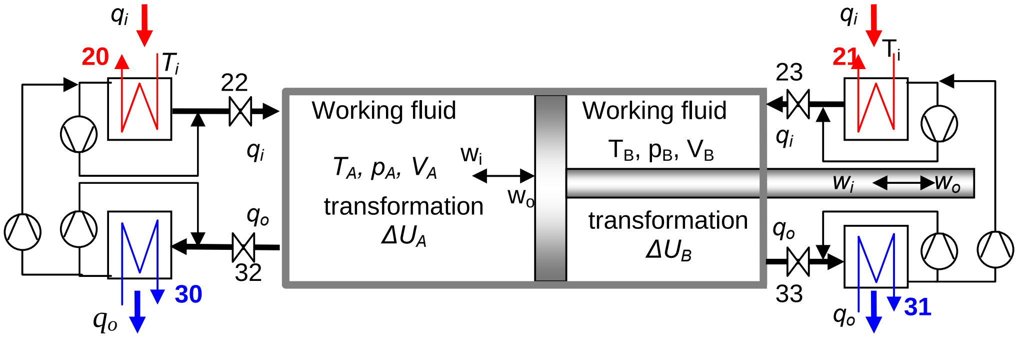
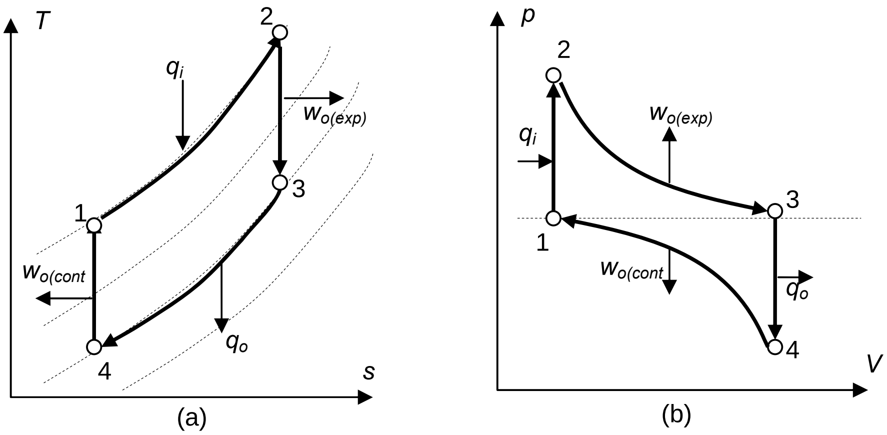


Fig. 3. The layout of heat work-interactions by means of double-acting reciprocating cylinders and heat transfer by means of forced convection.



(a) (b)

Fig. 4. T-s and p-V diagram of the thermal cycle for the cylinder chamber A.

Table 2. Path functions associated with the thermal cycle legs for both cylinder chambers A and B as shown in Fig. 3.

| **Cylinder chamber A** | | **Cylinder chamber B** | |
|---|---|---|---|
| **Cycle leg** | **Closed process based path function** | **Cycle leg** | **Closed process based path function** |
| 1–2 | Isochoric heat addition | 3-4 | Isochoric heat extraction |
| 2–3 | Adiabatic expansion ( work out) | 4-1 | Adiabatic contraction ( work out) |
| 3–4 | Isochoric heat extraction | 1-2 | Isochoric heat addition |
| 4–1 | Adiabatic contraction (work out) | 2-3 | Adiabatic expansion (work out) |

The processes associated with the cycle legs are described by means of Table 2, and the processes and the tasks of heat transfer carried out during the thermal cycle associated with both cylinder chambers A and B of the double acting cylinder are shown in Table 3.

Table 3. The processes and tasks carried during the thermal cycle associated with both cylinder chambers of the double acting cylinder considering the status of the inlet and outlet cylinder valves and its associated heat exchangers: isochoric heat addition and extraction -adiabatic expansion and contraction work as shown in Figs. 4 (a) and 4(b) undergoing the structure of Fig. 3

| **Left to right cylinder stroke motion** | |
|---|---|
| **Left cylinder chamber** | **Right cylinder. chamber** |
| Adiabatic expansion: reservoir (20), Valve (22). Isochoric heating reservoir (21) | Adiabatic contraction: reservoir (31), Valve (33). Isochoric cooling reservoir (30) |
| **Right to left to cylinder stroke motion** | |
| **Left cylinder chamber** | **Right cylinder chamber** |
| Adiabatic contraction: reservoir (30), Valve | Adiabatic expansion: reservoir (21), Valve (23) |

| | |
|---|---|
| (32). Isochoric cooling reservoir (31) | Isochoric heating reservoir (20) |

### 3.1. Data associated with the case study of a closed processes based four-legs thermal cycle that does useful work by adding and releasing heat

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 both adding and extracting heat at constant volume, the cycle points associated with the cycle parameters are shown in Tables 4, 5 and T-s and p-V diagrams of the thermal cycle depicted in Fig. 5, which shows the parameters of the quadrilateral cycle operating by adding and extracting heat in single acting mode. In this case, the engine structure corresponds to a reciprocating double acting cylinder depicted in Fig. 3.

Table 4. Cycle parameters of the four legs or quadrilateral cycle operating by heating and extracting heat in singe acting mode. The working fluid considered is air, and the thermodynamic properties data is achieved from NIST, the reference [16].

| State point | T(K) | u(kJ/kg) | s(kJ/kg.K) | p(kPa) | v(m3/kg) |
|---|---|---|---|---|---|
| 1 | 310 | 347.48 | 3.9244 | 100 | 0.88986 |
| 2 | 350.00 | 376.77 | 4.0118 | 112.93 | 0.88986 |
| 3 | 338.08 | 367.70 | 4.0118 | 100 | 0.97063 |
| 4 | 300.00 | 340.33 | 3.9259 | 88.717 | 0.97063 |
| State point | T(K) | u(kJ/kg) | s(kJ/kg.K) | p(kPa) | v(m3/kg) |
| 1 | 320 | 354.68 | 3.9564 | 100 | 0.91863 |
| 2 | 400.00 | 412.48 | 4.1158 | 125.05 | 0.91863 |
| 3 | 374.74 | 394.19 | 4.1158 | 100 | 1.07610 |
| 4 | 300.00 | 340.33 | 3.9555 | 80.024 | 1.07610 |
| State point | T(K) | u(kJ/kg) | s(kJ/kg.K) | p(kPa) | v(m3/kg) |
| 1 | 335 | 365.48 | 4.0026 | 100 | 0.96178 |
| 2 | 500.00 | 485.89 | 4.2945 | 149.34 | 0.96178 |
| 3 | 446.83 | 446.70 | 4.2945 | 100 | 1.28330 |
| 4 | 300.00 | 340.36 | 1.0033 | 67.106 | 1.28330 |
| State point | T(K) | u(kJ/kg) | s(kJ/kg.K) | p(kPa) | v(m3/kg) |
| 1 | 353 | 378.47 | 4.0554 | 100 | 1.01350 |
| 2 | 600.00 | 561.20 | 4.4468 | 170.08 | 1.01350 |
| 3 | 518.27 | 499.54 | 4.4468 | 100 | 1.48850 |
| 4 | 300.00 | 340.38 | 4.050 | 57.857 | 1.48850 |
| State point | T(K) | u(kJ/kg) | s(kJ/kg.K) | p(kPa) | v(m3/kg) |
| 1 | 370 | 390.76 | 4.1029 | 100 | 1.06240 |
| 2 | 700.00 | 638.81 | 4.5800 | 189.31 | 1.06240 |
| 3 | 589.01 | 552.87 | 4.5800 | 100 | 1.69180 |
| 4 | 300.00 | 340.39 | 4.10850 | 50.905 | 1.69180 |

Table 5. 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 |

## 4. ANALYSIS OF RESULTS AND DISCUSSION

In section 2, based on experimental observations, a partial set of closed processes based heat-work interaction modes were depicted. Among the possible heat-work interaction modes, a special one has been found which has not been previously considered, which consists of a sequence of two closed processes:

1- extracting heat at constant volume followed by
2- doing useful contraction work adiabatically.

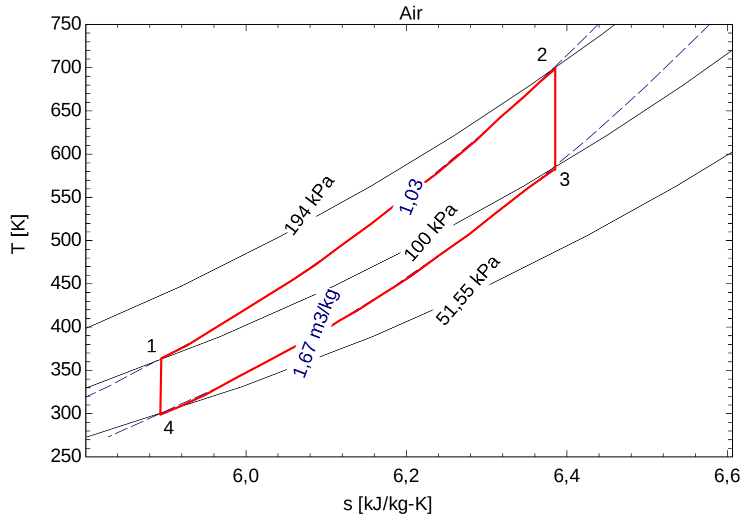


**Fig. 5** T-s diagram of the parameters of the quadrilateral cycle operating by heating and extracting heat in singe acting mode: cylinder chamber A.

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

Such an extraordinary phenomenon has never been taken into account before, and has severe implications for the energy balance of closed processes based cycles conducted by heat addition and heat extration according to observational evidence. Fortunately, such consequences imply a positive and significant impact with severe advantages, thanks to the effect obtaining useful work by releasing heat (useful work by a contraction based compression process), as the thermal efficiency is significantly increased. In order to reflect this phenomenon, as shown above, the general expression of the first law (energy balance) applied on closed processes based cycles has been extended according to Eqs. (4-7) to the following statement based on experimental observations through a proof of concept conducted by means of a test rig:

*Statement 1*

"The difference between added and extracted heat form a closed processes based thermal cycle that do work by adding and extracting heat is not the net work of this cycle"

*Statement 2*

"The net useful work of the closed processes based thermal cycle that do work by adding and extracting heat, where the work due to extracting heat is done by contraction based compression, is the results of adding the partial net works due to adding and extracting heat".

*Statement 3*

"The thermal efficiency is independent of the ratio of the heat source temperature to the heat sink temperatures"

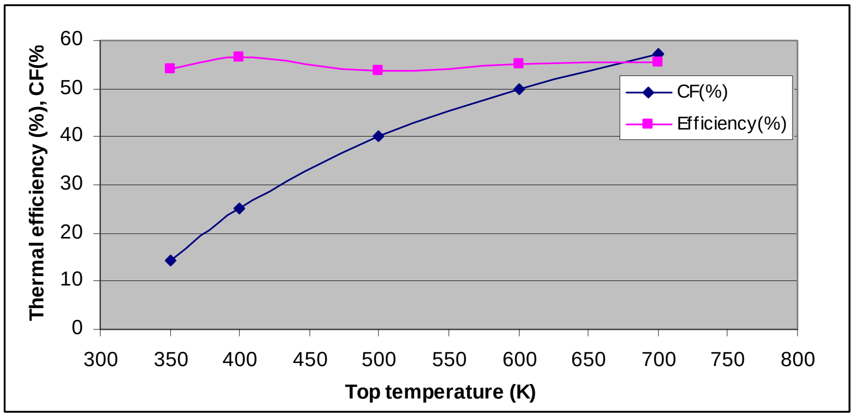


Fig. 6. Comparison of the thermal efficiency with Carnot efficiency as function of sevreal top operating temperatures.

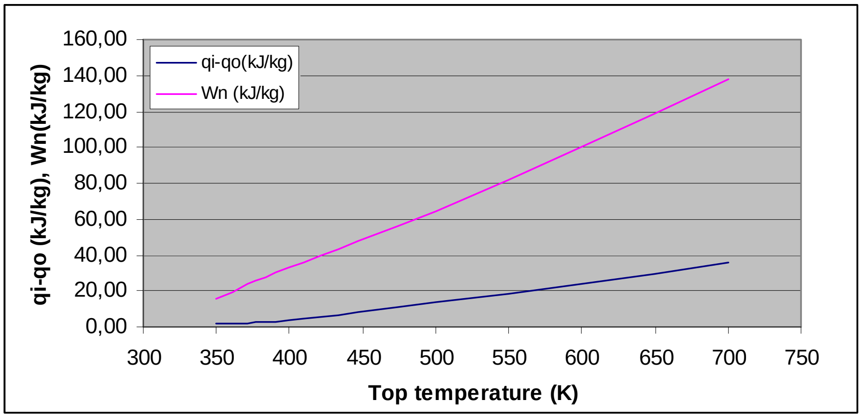


Fig. 7. The difference between ($q_i$-$q_o$) (a paramter defined by the difference between added and extracted heats) and the net work $w_n$ as function of sevreal top operating temperatures.

As consequence, statement 3 means that the thermal efficiency is not constrained by Carnot limitations. According to the results shown in Fig. 7, It must be noted that for low ratios of operating temperaures the diference betwnn added and extracted heat tends to zero, while the net work is independet of such paramter ($q_i$-$q_o$)

### 4.1. Discussion of results

From the equations deduced in the paper and based on the first principle, the results of the cycle analysis are depicted in Table 7, where results for 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 7 (a double acting heat in-out) exhibit an exceptional performance: High specific work and high thermal efficiency.

Table 6. 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 | $q_i$ | $q_o$ | $w_{o(exp)}$ | $\lvert w_i \rvert = w_{o(cont)}$ | $\Sigma \lvert w \rvert = w_n$ | $\eta_{th}$ |
|---|---|---|---|---|---|---|
| | kJ/kg | kJ/kg | kJ/kg | kJ/kg | kJ/kg | % |
| 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 6 depicts the performance of the studded thermal 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 7 is computed in line with Eqs. (4) and (7) for which $\Sigma w = w_n = w_o + |w_i|$. The thermal efficiency is computed taking into account that, in all cases, the extracted heat $q_o$ is extracted without any economic cost.

## 5. CONCLUSIONS

The heat-work interaction modes carried out in closed processes conducted by heat addition and heat releasing were analyzed in this paper. This analysis was inspired by the results of previous experiments, which found that, among the feasible heat-work interaction modes that occur in single closed process based transformations, there is one in which useful contraction based compression work is done while increasing the pressure, temperature and consequently its internal energy adiabatically. The consequences of this assertion based on observational evidence imply advantageous dramatic changes of the concept of performing useful mechanical work.

Three statements based on experimental evidence are presented, which radically change some fundamental concepts of physics, such as the first principle of thermodynamics applied to thermal cycles that exhibit the ability to perform mechanical work by contraction of a thermal working fluid because of the isochoric extraction of heat.

The analysis was performed on a double-acting cylinder operating according to a closed processes-based thermal cycle with air as working fluid. As explained along the description the thermal cycle operates in such a manner that it performs mechanical work by direct expansion due to heat addition, and by contraction based compression due to iochoric heat extraction. The cycle thermal efficiency according to the results of the case study operating between 300 K as the bottom temperature and a range of top temperatures that ranges 350-700 (K) with air yield an efficiency that approaches 55 %, while the specific work amounts approached 270 (kJ/kg). These results largely surpass the thermal efficiency of conventional thermal cycles operating bay adding heat only, and for top temperatures less athan 690 K surpass Carnot factor.

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-free (i.e. effective), and that most low-grade heat as well as waste heat costs are available at low cost, the widespread use of such technologies would contribute to reduce significantly the use of fossil fuels and consequently to the mitigation of golabl warming.

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