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The Behaviour of Some Working Fluids Applied on the Trilateral Cycles with Isothermal Controlled Expansion

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Authors' contributions

This work was carried out in collaboration between both authors. Author RFG designed the study, wrote the protocol, the first draft of the manuscript and managed literature searches. Author BFS managed the analyses of the study and literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

This work studies the behaviour of some working fluids to be applied on trilateral thermal cycles characterised by the conversion of heat into mechanical work undergoing controlled isothermal expansion path functions. The considered trilateral cycles are relevant because of its ability to operate at very high efficiency when the working fluid operates within the vicinity of its critical point. Strategies to keep a constant temperature along the expansion stroke of a single effect reciprocating engine undergoing a corresponding pressure to ensure the desired path function are proposed and validated.
An analysis of the trilateral cycle undergoing isothermal expansion has been carried out and the thermal efficiency compared with that of a Carnot engine operating under a similar ratio of temperatures. Results revealed that for some working fluids, there exists a special region in the vicinity of the critical point that exhibits the best conditions to achieve high thermal efficiency when the conversion of heat to mechanical work is carried out undergoing an isothermal expansion.

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Keywords: Carnot factor; isothermal expansion; load-dependent path functions; pressure-temperature dependence; trilateral cycle.

NOMENCLATURE

η	*thermal efficiency*
R	*perfect gases constant (kJ/kg-K)*
p	*pressure (bar)*
$qi=q_{23}$	*total specific input heat (kJ/kg)*
$q_o=q_{31}$	*specific rejected heat (kJ/kg)*
s	*specific entropy (kJ/kg-K)*
T	*temperature (K)*
u	*internal energy (kJ/kg)*
X_1	*Initial cylinder volume (m)*
X	*Fraction of the piston stroke(m)*
W	*specific work (isothermal TC) (kJ/kg)*

ACRONYMS

CF	*Carnot factor*
ICE	*Internal combustion engine*
Is	*Isobaric slope*
ORC	*Organic Rankine Cycle*
NORC	*Non organic Rankine Cycle*
TC	*Trilateral thermal cycle*

1. INTRODUCTION

Most of the conventional thermal cycles in use are based on the Carnot engine, consisting of cycles in which ideally heat is absorbed at high temperature (top temperature) to be expanded while performing mechanical work generally undergoing entropy generation due to irreversibilities to approach the bottom temperature. However in Fig. 1 a different concept of thermal cycles are proposed. The proposed cycles doesn't obey the Carnot statement and however, can be useful under certain operating conditions with some working. A brief history of the conventional thermal cycles undergoes a background concerning thermal cycles capable to operate with low temperature sources or low grade heat, including bottoming cycles. Thus, in the low temperature range, bottoming ORCs (organic Rankine cycles) constitute an interesting alternative to exploit the heat to power conversion cyckles, having shown good thermodynamic performance for bottoming cycles [1-2]. The interest in organic WFs for residual heat applications with low temperature Rankine cycles is an old technique that has been proposed for different applications such as renewable energy and low temperature heat recovery [3-7]. Recent advances concerning low grade heat sources applied to ORCs include the works of Wang and colleagues [8], who compared several WFs for low-temperature ORCs, concluding that R123 is the best choice for the temperature range of 100 to 180ºC and R141b is the optimal working fluid when the temperature is higher than 180ºC. In the same way, Jianqin and colleagues [9] proposed using an open steam power cycle for internal combustion (ICE) engine exhaust gas energy recovery. The authors concluded that the recovery efficiency of exhaust gas energy is mainly limited by exhaust gas temperature and ICE thermal efficiency can be improved by 6.3% at 6000 r/min.

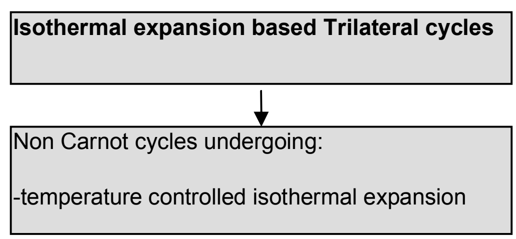


Fig. 1. Classification of Carnot and non Carnot based thermal engines including quadrilateral and trilateral thermal cycles (TCs)

Hua and colleagues [10] presented an ORC system used in ICE exhaust heat recovery, and a techno-economic analysis based on various WFs. They recovered a significant amount of ICE exhaust heat, which represented about one-third of the energy generated from the fuel by the ORC system. Results showed that R141b, R123 and R245fa present the highest thermal efficiency ranged from 16.60% to 13.30% and net power values from 60 to 49 kJ/kg. Jiangfeng and colleagues [11] conducted a study on low-temperature ORC which examined the effects of key thermodynamic design parameters, including turbine inlet pressure, turbine inlet temperature, pinch temperature difference and approach temperature difference in HRVG (heat recovery vapour generator), on the net power output and surface areas of both the HRVG and the condenser using R123, R245fa and isobutene. The results showed that turbine inlet pressure, turbine inlet temperature, pinch temperature difference and approach temperature difference had significant effects on the net power output and surface areas of both the HRVG and the condenser.

The study carried out by Dongxiang and colleagues [12] proposed an ideal ORC to analyse the influence in working fluid properties on thermal efficiency. The optimal operating conditions and exergy destruction for various heat source temperatures were also evaluated by means of pinch point analysis and exergy analysis. The results showed that different WFs have little impact on the optimal operating condition of ORC and selection of working fluid reasonably based on heat source temperature will help to optimise ORC performance.

During the last decade, growing interest has been observed in utilizing low and medium temperature heat sources, mainly due to its availability from oceans, solar, geothermal and industrial residual heat sources. Considering the field of heat to power conversion applications, conventionally ORCs (organic Rankine cycles) and Kalina cycles have been applied. And recently TCs (trilateral cycles) [13-15] are being implemented. Thus, for example, the TC performance has been researched for ammonia-water as working fluid in [14] and ORCs and TCs have been thermodynamically compared in [15]. The author presents a comparison of optimized systems with trilateral cycles with water as working fluid and optimized organic Rankine cycles, where the optimization criterion is the exergy efficiency for power production being the ratio of the net power output to the incoming exergy flow of the heat carrier. The author claims that the exergy efficiency for power production is larger by 14% - 29% for the trilateral cycle than for the ORC.

Whilst ORC and Kalina cycles are used already in existing power plants, the TC, although theoretically mature, it is still under technical development [13]. The components to implement a conventional TC are similar to those in the ORC system except that the working fluid at the entrance of the TC expander (turbine) is a saturated liquid. AS consequence, the state of the working fluid at the expander exit is a two-phase mixture. As the thermodynamic mean temperature at which heat is received is comparatively lower for the TC, the thermal efficiency for this cycle is lower than that for the ORC, for the same temperature limits. The performance of a trilateral cycle has been recently analysed in [16]. Also investigates and compares it with those for the ORC (organic Rankine cycle) and the Kalina cycle, focused on thermodynamics and thermo economics aspects. The results for the TC indicate that an increase in the expander inlet temperature leads to an increase in net output power and a decrease in product cost for this power plant, whereas this is not the case for the ORC system.

Quasi-isothermal compression based reciprocating engines as well as Quasi-isothermal expansion based power cycle engines have been recently developed. In this way, M.W. Coney et al. [17] presented the analysis of a novel concept for a high efficiency reciprocating internal combustion engine called as the isoengine and its cycle, where the maximum net electrical plant efficiency has been predicted to approach about 60% on diesel fuel and 58% on natural gas. They concluded that the key to the high electrical efficiency is the quasi-isothermal compression of the combustion air in cylinders, saving compression work and allowing the recovery of waste heat back into the cycle, mainly from the exhaust gas by means of a recuperator. On the other hand, Opubo N et al. [18] investigated some vapour power cycles for quasi-isothermal expansion instead of adiabatic expansion, taking advantage of the fact that quasi-isothermal expansion has the advantage of bringing the cycle efficiency closer to the ideal Carnot efficiency, with the drawback of requiring heat to be transferred to the working fluid as it expands. The authors claimed that the comparison the specific work output to more standard Stirling engines using gas is higher.

The research effort in this work is focused on trilateral thermal cycles operating under quasi-isothermal expansion instead of adiabatic expansion. Throughout this contribution it will be shown that for low relative operating temperatures the thermal efficiency exceeds the Carnot factor, which makes this thermal cycle very suitable for exploiting the heat to power conversion cycles with low grade residual heat.

However, in the present work the closed isothermal path functions carried out in the TCs, are appropriated to operate at relative low temperatures, being based on a completely different thermal cycle concept in comparison with the conventional Carnot based thermal cycles, not only structurally but also in terms of CF (Carnot factor) constraints, which can be surpassed in some particular operating conditions [19 - 20].

Thus, the objective of the study is to efficiently convert low temperature heat mainly from ocean thermal, solar thermal and low grade heat from industrial residual power sources by means of the proposed TCs into electric energy. As it has been indicated, the proposed conversion method is based on a different thermodynamic cycle: a non condensing mode closed processes based TC with or without regeneration. With this contribution, most of the low grade rejected heat may be converted into mechanical work at acceptable thermal efficiency by applying a TC whose thermal efficiency is not restricted by the CF such as mentioned in [19 - 20].

2. ANALYSIS OF THE TC UNDERGOING AN ISOTHERMAL EXPANSION

This section deals with the ideal transformations in terms of conversion heat into mechanical work that could be carried out in the presented closed processes based thermal cycles. In this way, the fact of introducing the concept of displacement work undergoes the movement of the piston in a cylinder from position i to position i+1, while volume changes from V_i to V_{i+1}, causing an amount of mechanical work W done by the system which is given as

$$W_{i-i+1} = \int_{V_i}^{V_{i+1}} p \cdot dV$$

In order to analyse the Isothermal ideal cases, let's consider the displacement of the piston under different path functions as shown in Fig. 2, for the following processes denoted as - Isothermal process (constant temperature)

Fig. 2, depicts the mechanical work performed under isothermal thermodynamic transformations when evolving from the state point i to the state point i+1, denoted as the state point 1 and state point 2 respectively.

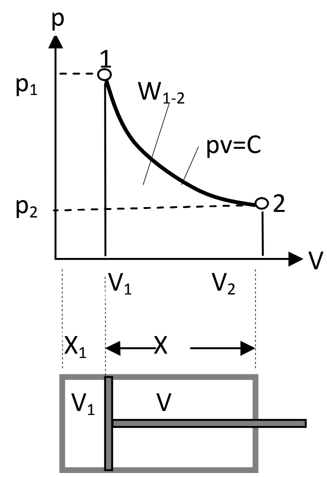


Fig. 2. Mechanical work performed undergoing an isothermal path function

2.1 The Mechanical Work Performed Under an Isothermal Path Function

According to the scheme depicted in Fig. 2, follows that the mechanical work performed by a piston along its full stroke can be described by means of a general expression as

$$W_{1-2} = \int_{V_1}^{V_2} p \cdot dV \tag{1}$$

Furthermore, considering a closed process undergoing an isothermal transformation, it follows that

$$p \cdot V = p_1 \cdot V_1 = p_2 \cdot V_2 \rightarrow \frac{V_1}{V_2} = \frac{p_2}{p_1} \rightarrow p = \frac{p_1 \cdot V_1}{V} = \frac{R \cdot T_1}{V} \tag{2}$$

thus the mechanical work delivered under an isothermal transformation is

$$W_{1-2} = p_1 \cdot V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1 \cdot V_1 \cdot Ln \frac{V_2}{V_1} = p_1 \cdot V_1 \cdot \ln \frac{p_1}{p_2} = R \cdot T_1 \cdot Ln \frac{p_1}{p_2} \tag{3}$$

The mechanical work described by Eq. (3) is realisable under the condition that the load (motion resistance) follows the profile defined by Eq. (2).

2.2 TC Undergoing an Isotherm Expansion Based Path Function

The proposed TC obeys the processes included between the state points defined in Table 1. In this way, Fig. 3 shows the T-s and p-V diagrams of a feasible TC undergoing a closed process based transformation for converting heat into mechanical work, where Fig. 3(a) and Fig. 3(b), depicts the isothermal transformation for the task of heat to work conversion.

According to the information provided by the Table 1 and the Fig. 3, the transformations associated to each path function of the TC are summarised as follows:

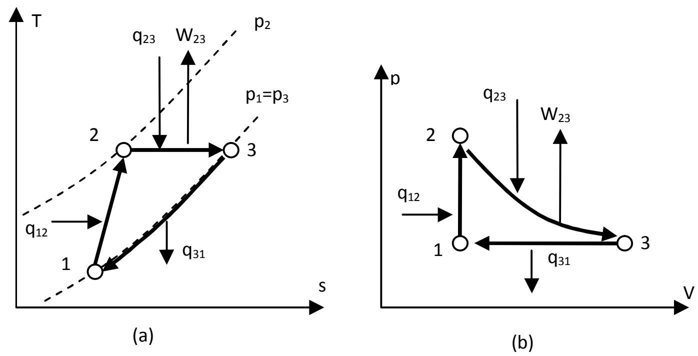


Fig. 3. The T-s and p-V diagrams of the TC undergoing a TC isothermal expansion for converting heat into mechanical work

Leg (1)-(2):

Correspond to a closed isochoric heating process. The amount of heat added from an external heat source at constant volume is

$$W_{12} = 0, \quad q_{12} = u_2 - u_1 = Cv \cdot (T_2 - T_1) \tag{4}$$

Leg (2)-(3):

Correspond, to a closed isothermal heating process. Consequently the internal energy remains constant so that the total heat added is converted into mechanical works since ideally there are not internal energy changes, and consequently,

$$u_{23} = 0, \tag{5}$$

Since $\dfrac{p_2}{p_1} = \dfrac{V_3}{V_1} = \dfrac{X_1 + X_3}{X_1} = 1 + \dfrac{X_3}{X_1}$

follows that

$$q_{23} = W_{23} = p_2 \cdot v_2 \cdot Ln(\frac{p_2}{p_1}) = R \cdot T_2 \cdot Ln(\frac{p_2}{p_1}) \tag{6}$$

which can be also expressed as function of the piston location (X) along the cylinder stroke according to the expression (7)

$$q_{23} = W_{23} = p_2 \cdot v_2 \cdot Ln(\frac{V_3}{V_1}) = R \cdot T_2 \cdot Ln\left[1 + \frac{X_3}{X_1}\right] \tag{7}$$

Leg (3)-(1):

Correspond to a closed isobaric process in which the working fluid is cooled. There is not mechanical work so that the rejected heat is coming from the internal energy according to the function

$$W_{31} = 0, \quad q_{31} = u_3 - u_1 = Cv \cdot (T_2 - T_1) = Cv \cdot (T_3 - T_1) \tag{8}$$

According to the expressions (7) - (9), the thermal efficiency of the TC undergoing a closed isothermal expansion is given as

$$\eta = 1 - \frac{q_o}{q_i} = 1 - \frac{q_{31}}{q_{12} + q_{23}} = 1 - \frac{q_{31}}{q_{13}} = \frac{W_{23}}{q_{13}} \tag{9}$$

Therefore the thermal efficiency of an isothermal expansion based TC can be expressed analytically, as

$$\begin{aligned} \eta &= \frac{W_{23}}{q_{13}} = \frac{W_{23}}{(u_2 - u_1) + W_{23}} = \frac{W_{23}}{Cv \cdot (T_2 - T_1) + W_{23}} = \\ &= \frac{R \cdot T_2 \cdot Ln\left[1 + \frac{X_3}{X_1}\right]}{Cv \cdot (T_2 - T_1) + R \cdot T_2 \cdot Ln\left[1 + \frac{X_3}{X_1}\right]} \end{aligned} \tag{10}$$

Since ideally the heat added to the transformation (2)-(3) is converted into mechanical work, the thermal efficiency defined in (11) exhibits a strong dependence on the difference of temperatures (T_2-T_1). Apparently, the thermal efficiency tends to the unity when such temperature difference tends to zero. However, real gases behaviour differs from this model.

Ideally a useful relation between Eq. (9) and CF, can be stated according to the following considerations:

Assuming CF as

$$CF = 1 - \frac{T_1}{T_2} = \frac{T_2 - T_1}{T_2}, \tag{11}$$

and the isothermal TC efficiency as

$$\frac{W_{23}}{Cv \cdot (T_2 - T_1) + W_{23}},$$

follows that

$$\eta = \frac{W_{23}}{W_{23} + T_2 \cdot Cv \cdot CF} \tag{12}$$

Eq. (12) provides a relation between the thermal efficiency and the CF for a TC. In fact, Eq. (12) suggest to us that for any amount of mechanical work W_{23} done, as T_2 increases, CF increases also according to Eq. (11), and consequently, according to Eq. (12), the isothermal TC efficiency η decreases and vice versa.

2.3 Conventional Results of the TC Undergoing an Isothermal Expansion Based Path Function

Table 1 shows the thermal efficiency of a TC as well as the corresponding CF, for carbon dioxide, nitrogen, helium and hydrogen as working fluids adapted from [20]. The results depicted in Table 2 have been achieved by assuming that the bottom temperature approaches the environment temperature (300 K). With such bottom temperature, a heat sink is always available, favouring the feasibility of an isothermal expansion based TC.

From the data attained as the results of the TC computation depicted in the Table 2, it can be highlighted that the fact of converting heat into work undergoing an isothermal path function is relevant in terms of thermal efficiency since the CF is surpassed for range of moderate top temperatures where the graded of residual heat cannot be used for alternative applications.

Nevertheless, as above demonstrated in next section, the thermal efficiency of the TC operating with the mentioned working fluids can be significantly increased. Such improvement can be achieved by finding the region of the TC in which the cycle is performed and undergoes the operating conditions such that the thermal efficiency could be improved.

3. THE REGION OF HIGH THERMAL EFFICIENCY IN THE VICINITY OF TRANSCRITICAL CONDITIONS

This section studies the region of high thermal efficiency for some working fluids undergoing isothermal expansion based path functions for converting heat into mechanical work. This region is characterised by the slope of isobars within the T-s diagram of each studied working fluid. Thus, when a working fluid is considered, it has been observed that the thermal efficiency is significantly high in a region of the T-s diagram near to the critical point where the slope of isobars tends to zero. In this region of the T-s diagram the slope of isobars (Is) approaches its minimum value.

The observation of this fact reveals that this important region corresponds with the vicinity of the critical point, in the supercritical region of the T-s diagram. For some working fluids this isobaric slope defined as

$$Is = dT / ds$$

approaches quasi-horizontal values. However, the slope satisfies the condition

$$Is = dT / ds > 0.$$

The availability of working fluids that satisfy such property consisting of exhibiting a very low slope in the supercritical vicinity of the critical point, contributes to the increment of the cycle work area when it has been achieved undergoing an isothermal path function, which contributes also to increase the TC thermal efficiency.

In the Figs. 6,7,8 and 9 it is shown the T-s diagrams of the region undergoing the minimum Is (isobaric slope) for carbon dioxide, helium, hydrogen and nitrogen as working fluids.

It must be noted that the region of maximum thermal efficiency is subjected to the particular critical point conditions. This limitation supposes a serious application constraint since the available residual heat based on a low grade heat source requires a specific working fluid such that matches the critical point conditions of the useful working fluid. That is, given the temperature of an available residual heat source, a working fluid with the critical point that matches with the heat source temperature must be found.

Table 1. The thermal efficiencies for some working fluids adapted from [20]

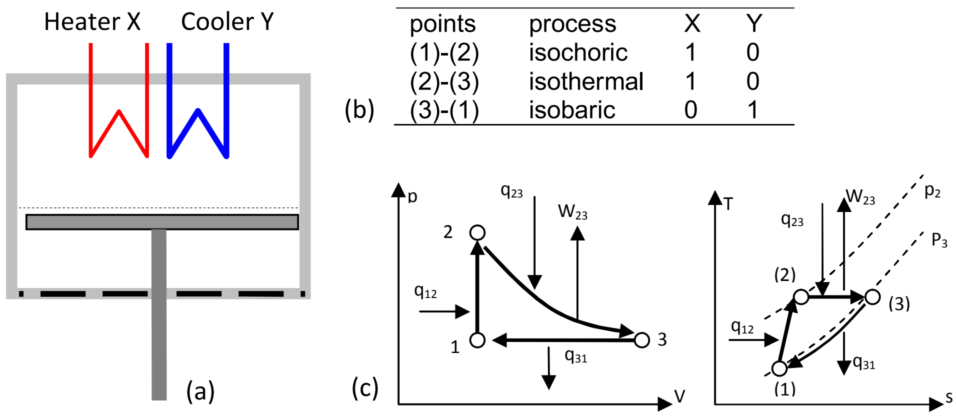
T_2(K)	η% (CO_2)	η% (N_2)	η% (He)	η% (H_2)	CF(%)
330	22,94	29,57	41,13	29,7	9,1
360	23,28	30,42	42,16	30,5	16,7
450	24,09	32,64	44,78	32,7	33,3
600	25,05	35,3	48,02	35,6	50

4. A CASE STUDY BASED ON THE TC

This section deals with the exploration and analysis of a case study in which a TC composed by closed systems based transformations is applied on the conversion of heat to mechanical work undergoing an isothermal expansion based path function.

The Fig. 4 represents a closed processes based TC implemented by means of a single effect cylinder in which Fig. 4(a) shows the single effect cylinder, Fig. 4(b), shows the sequence of processes carried out to complete the cycle, and Fig. 8(c) shows the corresponding p-V and T-s diagrams assuming isothermal expansion.

The TC shown In Fig. 4 consists of a single effect cylinder-actuator which could operate optionally with several working fluids including but not limited to carbon dioxide, helium, hydrogen and nitrogen, as well as other gases that remain at gaseous state at ambient temperature. The cylinder is equipped with heating and cooling facilities. The piston road could drive a reciprocating hydraulic pump for instance or any other load type. Although not analysed in this work and consequently not represented in Fig. 4, the possibility of regenerating some residual heat exits due to the fact that the residual heat



points	process	X	Y
(1)-(2)	isochoric	1	0
(2)-(3)	isothermal	1	0
(3)-(1)	isobaric	0	1

Fig. 4. A closed processes based TC implemented with a single effect cylinder. (a), single effect cylinder. (b), process sequence. (c), the p-V and T-s diagrams

corresponding to the working fluid temperature at the end of the expansion could be reused. Consequently, the possibility of increasing the thermal efficiency by regeneration is a real fact. The thermal cycle depicted in above Fig. 4 can be easily understood by observing the associated table as well as the p-V and T-s diagrams for a cycle with isothermal expansion.

In the associated table of Fig. 4 (b) the ports X and Y means the heater and cooler heat flows. Thus X=1 means that heat is entering to the cylinder, while Y=1 means that heat is being rejected from the cylinder to the environment. X=Y=0 indicates no heat transfer activity.

Considering the active chamber of the cylinder depicted in Fig. 4(a), and the T-s diagram shown also in the Fig. 4(c), the trilateral cycle starts in the state point 1, with a working fluid under a pressure, temperature, specific volume and entropy corresponding to the state point 1. After some heat has been added (q_{12}) at constant volume (isochoric process), the pressure, temperature and entropy corresponds to the state point 2. The transformation 2-3 undergoes constant temperature, so that the heat added (q_{22}) is converted integrally into mechanical work at constant temperature (isothermal process), since the internal energy remains constant along the transformation 2-3. The last transformation corresponds to the heat rejection q_{31} towards the heat sink which might be the environment.

As pressure decreases as consequence of the isothermal expansion, the mechanical load reacting against the piston rod is balanced to satisfy the condition of constant internal energy along the piston stroke until the bottom dead centre.

After expansion has finished in the state point (3), the piston initiates the way back towards the point (1) (the top dead centre) at constant pressure, while is being cooled, so that the cycle is completed.

4.1 Isothermal Expansion Control

The heat absorption rate by the working fluid (ideal gas) exhibits the ability for keeping an isothermal expansion process by modulating the heat absorption rate using properly control strategies. Under this assumption, such isothermal process has the ability to convert the total absorbed heat into mechanical work, since the internal energy remains constant due to the invariability of the process temperature. The proposed TC is also characterized by its ability to yield high efficiency at relative low temperatures. This is possible due to the inherent independence of the Carnot Statement.

4.2 Isothermal Process Control by Means of Heat Flow Rate Modulation

The transformation (2-3) undergoes constant temperature. This might be achieved by actuating on the heat flow as the piston moves along the cylinder stroke during the state point change (2-3), by measuring accurately the actual or real-time temperature to actuate on the heat rate by means of a properly adjusted control algorithm, according the scheme depicted in Fig. 5. In the case of high piston speed,

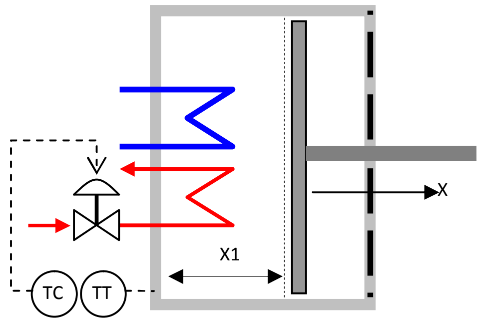


Fig. 5. A closed loop processes control to modulate the heat flow rate as function of the cylinder temperature

temperature cannot be accurately acquired so that the heat flow can be modulated on the basis of the corresponding cylinder pressure, where the cylinder pressure can be determined as function of the piston position. That is, knowing the piston position X, then the piston volume is also known as=A*X. Consequently, the corresponding pressure along this transformation can be described by

$$p = R^*T_2/A^*X. \tag{13}$$

Therefore, the pressure defined by Eq. (13) as function of the piston position, ensures an isothermal path function. However the direct measurement of the cylinder temperature during the isothermal expansion will ensure a more tight and accurate feedback control.

5. MAIN RESULTS OF THE ANALYSED CASE STUDY

As shown in Table 2, associated to the path functions depicted in the T-s diagram of the Fig. 4(c), as heat is being added to the cycle, entropy increases accordingly. However, the task of heat rejection (state point's change 3-1) undergoes the recovering of the initial conditions so that the TC is balanced to fulfil second law.

In Table 3, it is shown the main results of the TC operating with CO_2, He, H_2 and N_2 as working fluids undergoing an isothermal expansion. The characteristics of the data necessary to analyse the TC, have been achieved from [21], which consists of a standard database.

On the basis of the data presented in Table 3 regarding to temperature, pressure, entropy, internal energy, specific volume and specific heat at constant pressure and constant volume for each state point, the TC for the mentioned working fluids has been analysed. The results concerning to thermal efficiency, specific work and CF has been presented.

Thus, considering the results concerning to carbon dioxide, follows that the thermal efficiency, specific work and CF approaches the values of 76.34%, 473.6 kJ/kg and 7.69% at a top temperature of 325 K. Comparing the thermal efficiency of the case study with the results achieved from the TC described in Table 1 for carbon dioxide adapted from [20], 25% and CF, 50% at a top temperature of 600 K follows that a relevant difference exists.

Similar considerations must be taken into account for the rest of analysed working fluids (helium, hydrogen and nitrogen). However, the feasibility of the TC operating with these working fluids depends on the heat sink temperature, since for such fluids this temperature must be lower than 6 K for helium, 34 K for hydrogen and 130 K for nitrogen. This consideration supposes a serious constraint regarding its practical application in such restrictive conditions, due to the environmental temperature limitations.

For these reasons, the TCs of the case study operating with helium, hydrogen or nitrogen,

Table 2. Second law verification and entropy balance for the TC operating with CO_2, He, H_2 and N_2 as working fluids undergoing a closed isothermal expansion process

(i)-(i+1)	TC undergoing an Isothermal heat to work conversion process	ΔS = S(i+1) - S(i)	2^d law verification	Σ(Δs) = 0
		CO_2		
(1)-(2)	isochoric (heat addition)	1.01150 – 0.92976 = 0.08175	0.0817 5> 0	0.0817 5
(2)-(3)	isothermal (heat addition)	0.92975 – 0.87759 = 0.05216	0.05216 > 0	+0.05216
(3)-(1)	isobaric (heat rejection)	0.87759 – 1.01150 = -0.13391	-0.13391 < 0	-0.13391 = 0
		He		
(1)-(2)	isochoric (heat addition)	4.4500 – 2.2200 = 2.2300	2.2300> 0	2.2300
(2)-(3)	isothermal (heat addition)	8.5500 – 4.4500 = 4.1000	4.1000 > 0	+4.1000
(3)-(1)	isobaric (heat rejection)	2.2200 – 8.5500 = -6.3300	-6.3300 < 0	-6.33 = 0
		H_2		
(1)-(2)	isochoric (heat addition)	10.0530 – 8.8565 = 1.1965	1.1965 > 0	1.1965
(2)-(3)	isothermal (heat addition)	16.324 – 10.0530 = 6.271	6.271 > 0	+6.271
(3)-(1)	isobaric (heat rejection)	8.8565 – 16.324 = -7.4675	-7.4675 < 0	-7.4675 = 0
		N_2		
(1)-(2)	isochoric (heat addition)	4.3781 – 4.2804 = 0.0977	0.0977 > 0	0.0977
(2)-(3)	isothermal (heat addition)	4.7323 – 4.3781 = 0.3542	0.3542> 0	+0.3542
(3)-(1)	isobaric (heat rejection)	4.2804 – 4.7323 = -0.4519	-0.4519< 0	-0.4519 = 0

Table 3. Main results of the TC operating with CO_2, He, H_2 and N_2 as working fluids undergoing an isothermal expansion

					CO2					
point	**T(K)**	**u (kJ/kg)**	**s (kJ/kg-K)**	**p(bar)**	**v(m³/kg)**	**Cv (kJ/kg-K)**	**Cp (kJ/kg-K)**	**η(%)**	**W (kJ/kg)**	**CF(%)**
1	300	263.16	1.2389	75	0.0013626	1.0115	4.5507	76.34	473.6	7.69
2	325	287.15	1.3157	173.6	0.0013626	0.92975	2.6663			
3	325	409.93	1.8115	75	0.0052833	0.87759	2.0648			
					He					
point	**T(K)**	**u (kJ/kg)**	**s (kJ/kg.K)**	**p(bar)**	**v (m3/kg)**	**Cv (kJ/kg.K)**	**Cp (kJ/kg.K)**	**η(%)**	**W (kJ/kg)**	**CF(%)**
1	6	9.40	2.22	4	0.01245	2.823	17.880	70.8	79.1	53.5
2	12.909	29.65	4.45	20	0.01245	3.061	6.869			
3	12.909	41.98	8.55	4	0.06406	3.123	5.7694			
					H_2					
point	**T(K)**	**u (kJ/kg)**	**s (kJ/kg-K)**	**p(bar)**	**v (m³/kg)**	**Cv (kJ/kg-K)**	**Cp (kJ/kg-K)**	**η(%)**	**W (kJ/kg)**	**CF(%)**
1	34	236.77	8.8565	15	0.027277	7.6149	146.47	79.5	722.7	15.3
2	40.16	280.97	10.053	30	0.027277	6.9008	32.863			
3	40.16	422.57	16.324	15	0.081575	6.7065	18.454			
					N_2					
point	**T(K)**	**u (kJ/kg)**	**s (kJ/kg-K)**	**p (bar)**	**v (m³/kg)**	**Cv (kJ/kg-K)**	**Cp (kJ/kg-K)**	**η(%)**	**W (kJ/kg)**	**CF(%)**
1	130	26.253	4.2804	40	0.003334	1.2065	18.394	82.11	209.3	8.8
2	142.55	39.535	4.3781	60	0.003334	0.97052	4.5921			
3	142.55	71.847	4.7323	40	0.00709	0.8887	2.3173			

provides a thermal efficiency of 70.8%, 79.5 % and 82 % respectively, while for a feasible cycle operating with a bottom temperature of 300 K the thermal efficiency according Table 1 is 41.13 % for helium, 29.7 % for hydrogen and 29.57 % for nitrogen. The above discussion highlights the fact that the research interest should be centred on finding working fluids characterised by its capacity to operate with bottom temperature slightly higher than the temperature of the available heat sink, while satisfying the condition of a low isobaric slope in the T-s diagram of the considered TCs, such as carbon dioxide for instance.

The data represented in Table 3 for each working fluid of the TCs is graphically depicted in Figs. 6 to 9 for the corresponding working fluid. The associated temperature and entropy of each state point is represented and the layout of the T-s diagrams shown. The isobars help us to distinguish the region of low isobaric slopes.

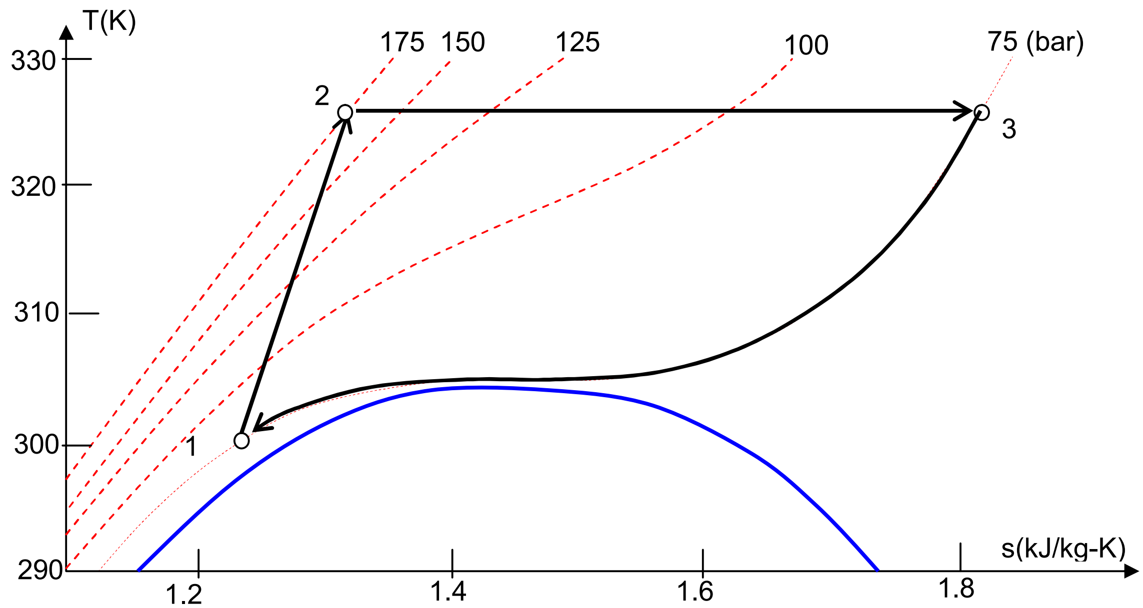


Fig. 6. T-s diagram for CO_2 as working fluid, operating in the region of low isobaric slopes above the critical point, for which the slope of the isobars (dT/ds) approaches zero

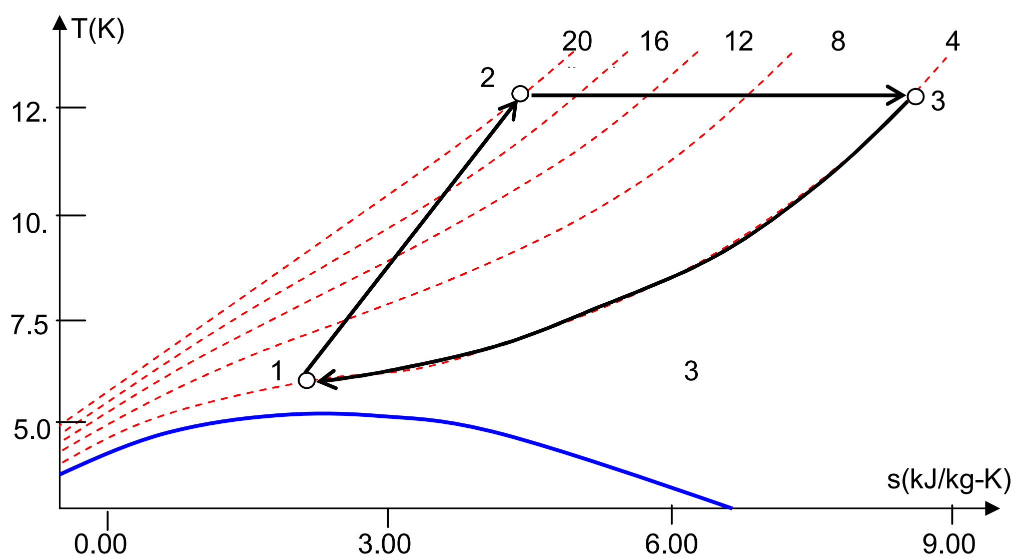


Fig. 7. T-s diagram for He as working fluid, operating in the region of low isobaric slopes above the critical point, for which the slope of the isobars (dT/ds) approaches zero

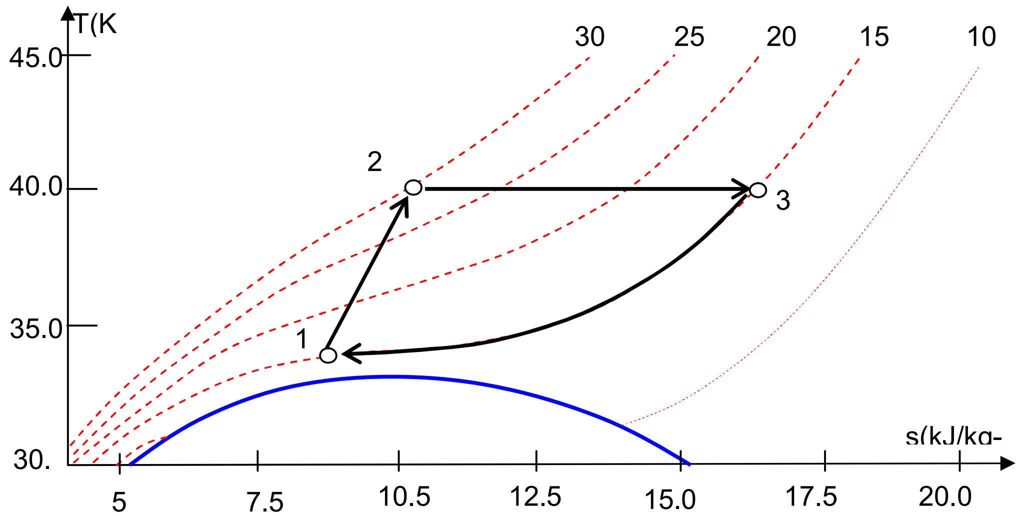


Fig. 8. T-s diagram for H_2 as working fluid operating in the region of low isobaric slopes above the critical point, for which the slope of the isobars (dT/ds) approaches zero

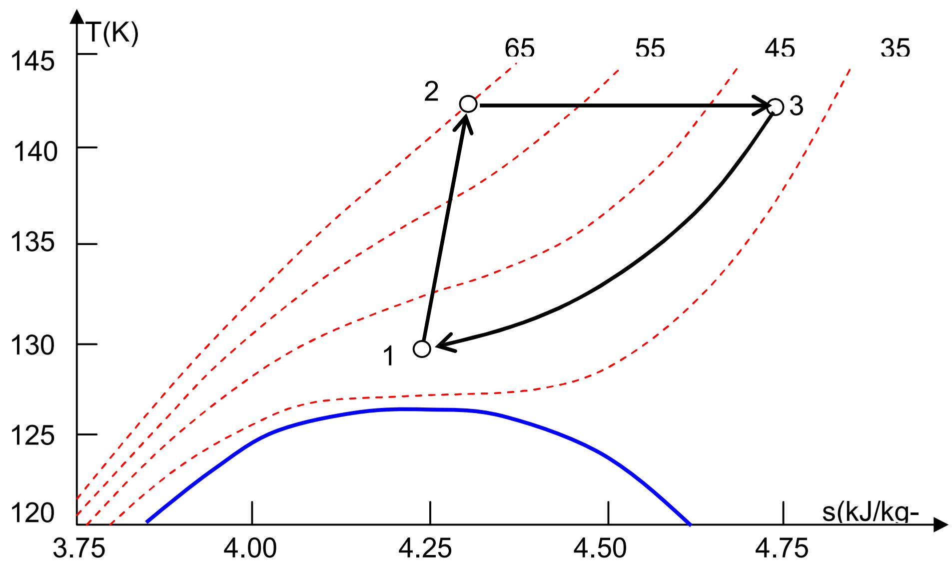


Fig. 9. T-s diagram for N_2 as working fluid operating in the region of low isobaric slopes above the critical point, for which the slope of the isobars (dT/ds) approaches zero

6. CONCLUSION

The behaviour of some working fluids to be applied on trilateral thermal cycles characterised by the conversion of heat into mechanical work undergoing controlled isothermal expansion based path functions has been presented. The scope of this analysis includes the study of cases in which thermal working fluids such as carbon dioxide, helium, hydrogen and nitrogen have been considered.

The objective of the study consisted in demonstrate that high thermal efficiency can be achieved by selecting working fluids characterized by its operating conditions. That is, suitable to operate in the vicinity of the supercritical point near the critical point, for which the slope of the isobars in a T-s diagram approaches low values.

The study proved the ability of TC to meet the necessary conditions to obtain high thermal efficiency based on the trilateral cycle operating undergoing slightly supercritical conditions.

The achieved thermal efficiencies approached respectively 76.34% for carbon dioxide, 70.8%, for helium, 79.5% for hydrogen and 82% for nitrogen, with relative moderate top temperatures.

An important drawback concerning the TCs is due to the required feedback control system to ensure constant temperature during the expansion along the piston stroke by means of modulating the inlet heat flow rate.

From the analysis of the case study it can be highlighted also the independence of the thermal efficiency with respect to the CF, as well as the high thermal efficiency at low top temperatures with respect to CF.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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