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A THEMODYNAMIC MODEL FOR ANALYSIS AND SELECTION OF A WORKING FLUID FOR AN ORGANIC RANKINE CYCLE WITH AN OPEN FEEDING FLUID HEATER

UM MODELO TERMODINÂMICO PARA ANÁLISE E SELEÇÃO DE UM FLUIDO DE TRABALHO PARA UM CICLO RANKINE ORGÂNICO COM UM AQUECEDOR DE FLUIDO DE ALIMENTAÇÃO ABERTO

UN MODELO TERMODINÁMICO PARA EL ANÁLISIS Y SELECCIÓN DE UN FLUIDO DE TRABAJO PARA UN CICLO RANKINE ORGÁNICO CON UN CALENTADOR DE FLUIDO DE ALIMENTACIÓN ABIERTO

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ABSTRACT

The purpose of this study is to develop multiple linear regressions able to express the cycle thermal efficiency (CTE) from selected operating parameters for all organic fluid categories within several thermodynamic cycles. The present study also purposes the fluid selection considering the CTE results obtained through the developed model. The results provided by the statistical data allow to affirm the validity of the developed method, with high adjusted R-square values and low estimated deviation values. Wet fluids presented CTE average deviations equal to 0.38% for subcritical cycle and 0.45% for supercritical cycle. Dry fluids presented CTE average deviation of 0.83% in subcritical cycle and 0.61% for the supercritical cycle. Isentropic category presented 1.04% of CTE average deviation for the supercritical cycle and 0.68% for

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subcritical and superheated cycles. The calculation of the CTE absolute mean error provided values even smaller than the CTE estimated deviation provided earlier by the statistical analyze. Thus, a general absolute mean error equal to 0.6414% confirms the multiple linear regression method accuracy. The validation for the fluid selection method regards to a comparison between the best CTE sequence produced by the thermodynamic method and the best CTE sequence produced by the multiple linear regression method.

Keywords: Cycle Thermal Efficiency (CTE). Organic Rankine Cycles. Organic Fluids. Multiple Linear Regression. Fluid Selection. Operating Parameters.

RESUMO

O objetivo deste estudo é desenvolver regressões lineares múltiplas capazes de expressar a eficiência térmica do ciclo (ETC) a partir de parâmetros operacionais selecionados para todas as categorias de fluidos orgânicos em diversos ciclos termodinâmicos. O presente estudo também visa a seleção do fluido considerando os resultados de ETC obtidos por meio do modelo desenvolvido. Os resultados fornecidos pelos dados estatísticos permitem afirmar a validade do método desenvolvido, com altos valores de R² ajustado e baixos valores de desvio estimado. Fluidos úmidos apresentaram desvios médios de ETC iguais a 0,38% para o ciclo subcrítico e 0,45% para o ciclo supercrítico. Fluidos secos apresentaram desvio médio de ETC de 0,83% no ciclo subcrítico e 0,61% para o ciclo supercrítico. A categoria isentrópica apresentou desvio médio de ETC de 1,04% para o ciclo supercrítico e 0,68% para os ciclos subcrítico e superaquecido. O cálculo do erro médio absoluto da ETC forneceu valores ainda menores do que o desvio estimado da ETC fornecido anteriormente pela análise estatística. Assim, um erro médio absoluto geral de 0,6414% confirma a precisão do método de regressão linear múltipla. A validação do método de seleção de fluidos refere-se à comparação entre a melhor sequência de CTE produzida pelo método termodinâmico e a melhor sequência de CTE produzida pelo método de regressão linear múltipla.

Palavras-chave: Eficiência Térmica do Ciclo (CTE). Ciclos Rankine Orgânicos. Fluidos Orgânicos. Regressão Linear Múltipla. Seleção de Fluidos. Parâmetros Operacionais.

RESUMEN

El propósito de este estudio es desarrollar regresiones lineales múltiples capaces de expresar la eficiencia térmica del ciclo (CTE) a partir de parámetros operativos seleccionados para todas las categorías de fluidos orgánicos dentro de varios ciclos termodinámicos. El presente estudio también propone la selección del fluido considerando los resultados de CTE obtenidos mediante el modelo desarrollado. Los resultados proporcionados por los datos estadísticos permiten afirmar la validez del método desarrollado, con altos valores de R-cuadrado ajustado y bajos valores de desviación estimada. Los fluidos húmedos presentaron desviaciones promedio de CTE iguales al 0,38 % para el ciclo subcrítico y al 0,45 % para el ciclo supercrítico. Los fluidos secos presentaron una desviación promedio de CTE del 0,83 % en el ciclo subcrítico y del 0,61 % para el ciclo supercrítico. La categoría isoentrópica presentó una desviación promedio de CTE del 1,04 % para el ciclo supercrítico y del 0,68 % para los ciclos subcrítico y sobrecalentado. El cálculo del error medio absoluto de CTE arrojó valores incluso menores que la desviación estimada de CTE proporcionada previamente por el análisis estadístico. Por lo tanto, un error medio absoluto general igual al 0,6414 % confirma la precisión del método de regresión lineal múltiple. La validación del método de selección de fluidos se basa en una comparación entre la mejor secuencia de CTE generada por el método termodinámico y la mejor secuencia de CTE generada por el método de regresión lineal múltiple.

Palabras clave: Eficiencia Térmica del Ciclo (CTE). Ciclos Rankine Orgánicos. Fluidos Orgánicos. Regresión Lineal Múltiple. Selección de Fluidos. Parámetros de Operación.

INTRODUCTION

Considered a reliable means of energy production, the organic Rankine cycle (ORC) is a technology that allows the conversion of thermal energy in electricity from low temperatures, obtained from the burning of fuels through a heat system (Tartière and Astolfi, 2017). The main characteristic of this cycle regards to the use of an organic fluid, replacing the water, usually used in conventional Rankine cycles. In this process, the fluid also undergoes through a heat operation turning into steam, promoting the energy generation in the turbine. Besides, the use of an organic fluid allows the system to obtain electricity from lower temperatures, when compared to the conventional Rankine cycle, due to the boiling point of these fluids (lower than the water). Pressure and temperature present an important role for ORC's thermal efficiency. Values of critical pressure and critical temperature must be considered for the using of organic fluids and related calculations. In this study, dimensionless pressure and dimensionless temperature were considered as a reference for the calculation development and results exposition.

Lecompte *et al.* (2015) presents an organic Rankine cycle (ORC) as a similar model to the conventional Rankine cycle, where the main difference regards to the working fluid. In ORC technology, an organic working fluid is select, replacing the conventional fluid (water). A careful selection of the working fluid allows the system to convert heat in electrical energy from low temperatures (lower when compared to temperatures used for conventional fluids in conventional Rankine cycles).

Rayegan and Tao (2011) classified the organic fluids used in Rankine cycles as dry, wet and isentropic. This classification regards to the *T-s* diagram slope, which presents peculiarities for each fluid category. Wang *et al.* (2013) detail the *T-s* slope format that defines each organic fluid. According to the authors, dry fluids presents a positive saturation slope, while the wet fluids presents a negative saturation slope. Isentropic fluids have the infinite saturation slope as its main characteristic. Another important aspect of the ORC regards to the use of alternative heat sources for the heating operation in the evaporator, discarding the need to burn fossil fuels (Javanshir and Sarunac, 2017). According to Mago *et al.* (2008), ORC is an alternative technology that can be considered an environmental friendly solution for the problems related to thermal pollution and burning of fossil fuels. The authors describe the coverage of the ORC's systems, which includes the recovering of waste heat, geothermal applications, solar plants, biomass and many others.

The basic architecture of an ORC consists in a feed pump, an evaporator, a turbine connected with a generator and a condenser, that is, the same composition of a conventional Rankine cycle. The process begin in the feed pump, where the fluid is compressed and sent to the evaporator, which performs a heat process until the phase change, from liquid to steam. Entering the turbine, an expansion process starts, and after that, the fluid is sent to the condenser, where a new phase change occurs, but this time, transforming steam into liquid, unlike the first transformation. The cycle meets it´s end when the fluid is sent to the first point, the feed pump, where the process starts over again (Roy and Misra, 2012).

According to Chen, Xu and Chen (2012) the currently researches around ORC technology can be classified into five types: (1) modifying of ORC architecture in order to obtain higher thermal efficiencies; (2) fluid selection; (3) replacement of subcritical ORC's for supercritical ORC's; (4) using of zeotropic mixture as working fluids and (5) reach of optimal operating conditions. All these initiatives aim at obtaining higher thermal performance for the cycle. Dai, Wang and Gao (2009) wrote about the several parameters of influence over the ORC performance. The authors also mentioned the relation between these parameters and its joint influence over the system, comparing it to a multidimensional surface, which can be optimized in order to obtain a better thermal performance.

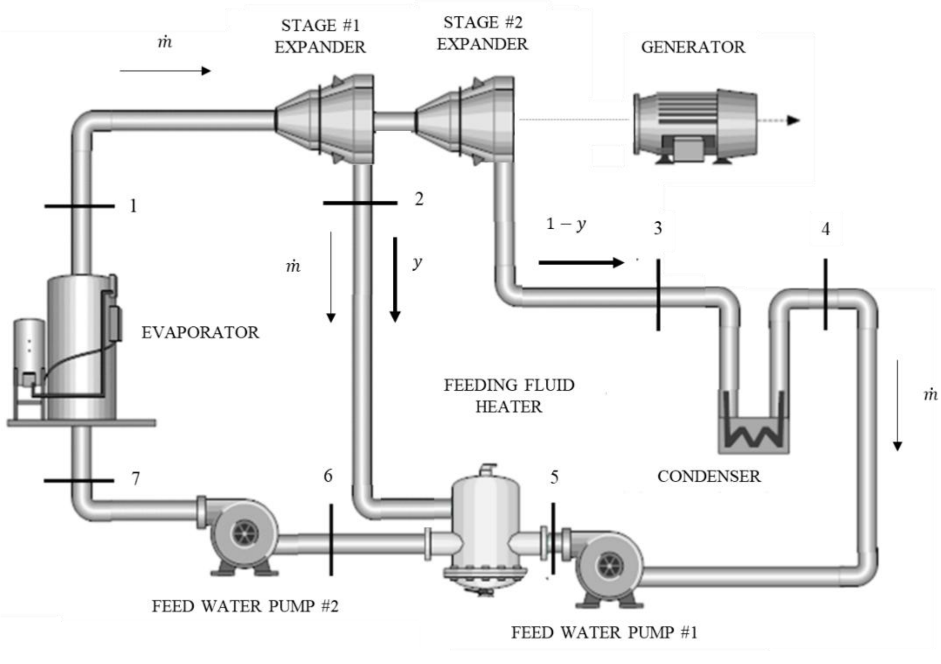
The main purpose of this paper is to develop a mathematical model (multiple linear regression) able to express the cycle thermal efficiency (CTE) for each working fluid category within several thermodynamic cycles (subcritical, subcritical with superheating and supercritical) from the operating parameters established. The present study also purposes a method to perform the working fluid selection within each thermodynamic cycle, considering the CTE results obtained through the mathematical model developed. Lastly, a comparison between the CTE results obtained from the thermodynamic method and the CTE results obtained from the multiple linear regression is required in order to validate the latter method.

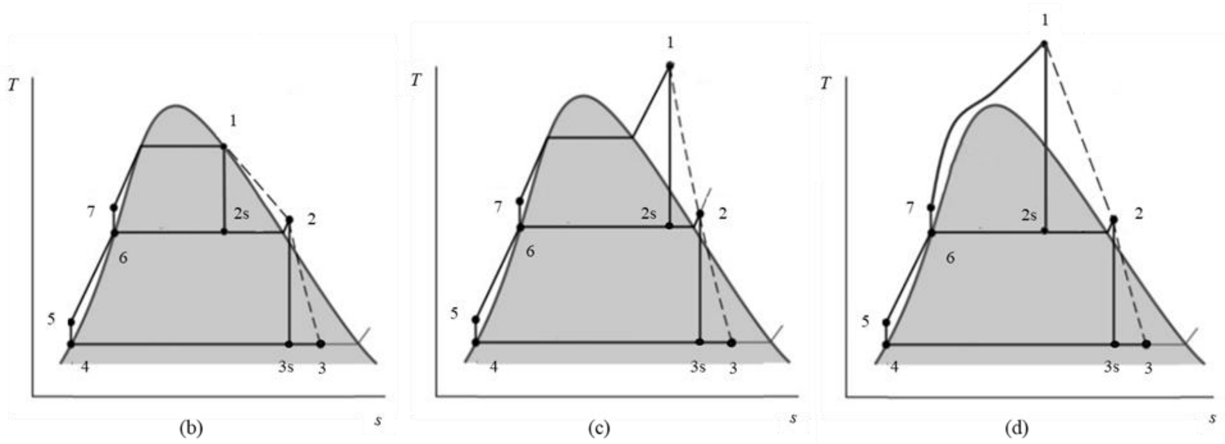
THERMODYNAMIC MODEL

For the development of this study, three thermodynamic cycle were considered for the regenerative organic Rankine model (RORC): subcritical, subcritical with superheating and supercritical. The models described can be seen in Fig. 1:

Figure 1

(a) Architecture of a subcritical regenerative ORC and T-s diagram for subcritical (a), subcritical with superheating (b) and supercritical (c) regenerative ORC.





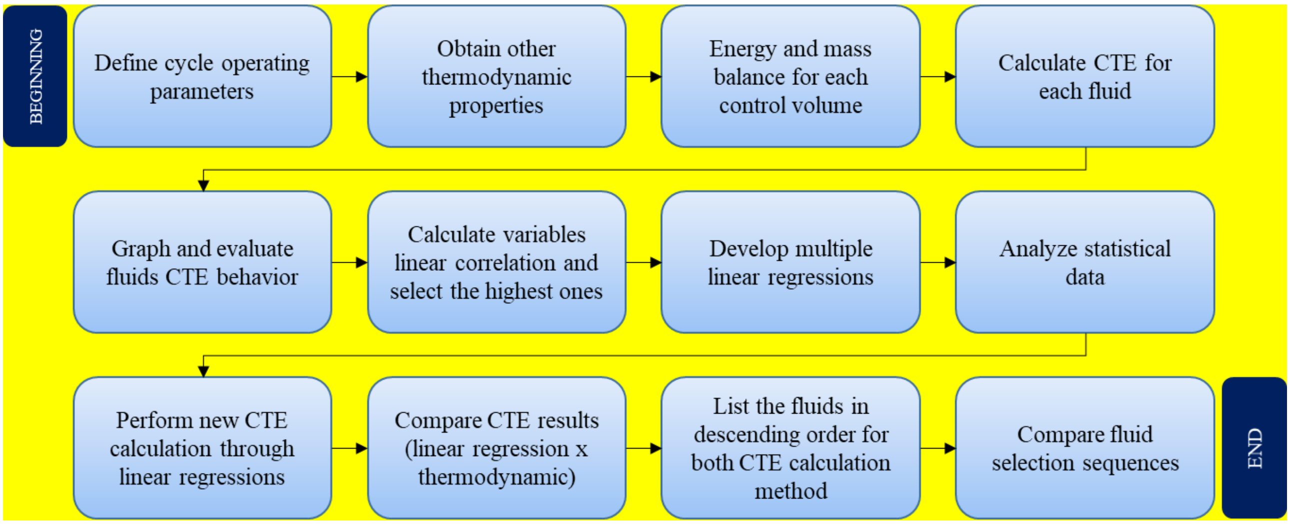
Adapted from: Xi *et al.* (2013).

MATERIALS AND METHOD

The steps for development of this study can be seen in Fig. 2. Definition of the operating parameters and its ranges, such as evaporator temperature, feeding fluid heater pressure and condenser temperature represents the first step for obtaining all the other control volume properties required to a thermodynamic analysis. Then, energy and mass balance can be performed for each control volume in order to obtain the thermodynamic expressions to reach CTE values for each operating parameters range. A subsequent graph representation was performed to allow the initial understanding about the CTE fluids behavior. At this point, it is possible to evaluate the influence of operating parameters over the CTE results for each fluid within each thermodynamic cycle. After that, a statistical analysis starts, beginning by the variables linear correlation, that is, to measure the influence level of each operating parameter over the CTE results. This evaluation meets the graph analysis previously performed and allow the selection of cycle most significant variables with the aim of writing CTE expression according to them. Thus, using the selected variables and CTE results obtained through the thermodynamic method, it is possible to develop expressions know as multiple linear regression. These expressions allow the calculation of CTE values for each working fluid and working fluid category within each thermodynamic cycle through the simple replacement of the operating parameters values. An additional analyze shall be performed in order to evaluate the estimated deviation values (standard error) provided by the calculation and also the adjusted R-square, which denotes the operating parameters joint influence level (percentage) over the CTE result. In sequence, a new CTE calculation is performed through the multiple linear regression expressions, for each fluid within each thermodynamic cycle. Later, a comparison between the CTE results obtained through the multiple linear regression and the CTE results obtained through the thermodynamic method is performed, with the aim of validate the developed expressions. Lastly, a fluid selection list is write, according to the CTE results, from best to worst. The comparison between the fluid sequence provided by the multiple linear regression and the fluid sequence provided by the thermodynamic method is considered to validate the fluid selection through the developed method.

Figure 2

Flowchart for study development.



Operating Parameters

Through the dimensionlessness concept used in the studies published by Wang *et al.* (2011) and by Javanshir and Sarunac (2017), the operation parameters values for the evaporator and for the feeding fluid heater were defined.

The dimensionless pressure can be expressed by the ratio between the operation pressure and the fluid critical pressure, similarly to the dimensionless temperature, which denotes the ratio between the operation temperature and the fluid critical temperature. Dimensionless pressure can express by the Eq. 1. and dimensionless temperature by the Eq. 2.

$$P_r = \frac{p}{p_{cr}} \qquad (1)$$

$$T_r = \frac{T}{T_{cr}} \qquad (2)$$

Ranges for dimensionless pressure and for dimensionless temperature were adopted in order to obtain several values for operating parameters and subsequent several results for the Cycle Thermal Efficiency (CTE), also considering the critical properties for each organic fluid used in the calculations. Besides that, based on the study of Kuo, *et al.* (2011), all possible parameters combination were performed in order to obtain the results for its joint influence over the CTE. Thus, 9 variable combinations were performed for each cycle considered in this study, as can be seen in tab. 1.

Table 1

Operating parameters for each thermodynamic cycle.

Cycle	Evaporator		Regenerator (Feed fluid heater)	Condenser
Subcritical	$P_{r,1}$ = 0.85		$P_{r,1}$ = 0.50	288.15K
	$P_{r,2}$ = 0.90		$P_{r,2}$ = 0.60	
	$P_{r,3}$ = 0.95		$P_{r,3}$ = 0.70	
Subcritical with superheat	$P_{r,1}$ = 0.95	$T_{r,1}$ = 1.10	$P_{r,1}$ = 0.50	288.15K
		$T_{r,2}$ = 1.20	$P_{r,2}$ = 0.60	
		$T_{r,3}$ = 1.30	$P_{r,3}$ = 0.70	
Supercritical	$P_{r,1}$ = 1.35	$T_{r,1}$ = 1.25	$P_{r,1}$ = 0.50	288.15K
		$T_{r,2}$ = 1.30	$P_{r,2}$ = 0.60	
		$T_{r,3}$ = 1.35	$P_{r,3}$ = 0.70	

Thermodynamic Analysis

All the other cycle properties were obtained through the application of the first thermodynamic law for each control volume, considering the operating parameters previously listed.

Several mathematical simulations were performed in order to obtain the results of Cycle Thermal Efficiency (CTE). The calculations considered the evaporator and the feeding fluid heater parameters as the main variables for the cycle, as a steady temperature for the cold source.

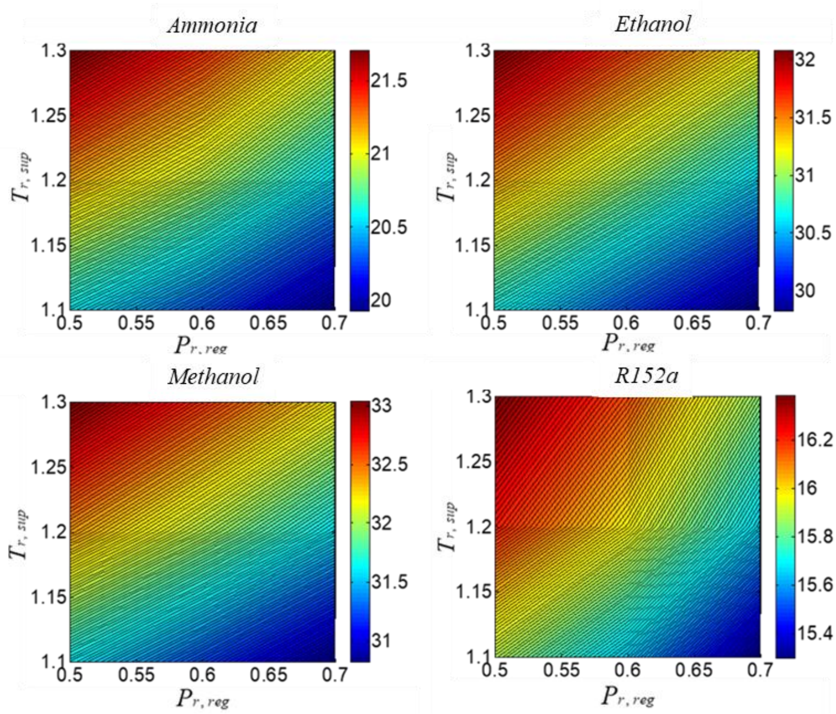
Through the results obtained from the mathematical simulations, graphical representations were developed to express the CTE behavior, according to the operation parameters. Some CTE results for wet fluids working in a subcritical cycle with superheating can be seen in Fig. 3. Complete graphic results representation are available in appendix.

Through the analysis of the graphic representations for the subcritical cycle, we can observe a direct proportionality between the CTE and the evaporator pressure for the wet fluids considered in this study. A descrease of the CTE can be seen when an increase of the FFH pressure occours, for the same classification of working fluids. The categogy dry fluids divides itself in two completely different behavior, related to the CTE. Isobutane, Isopentane, R227ea and R245fa presented a behavior very close to the wet fluids, with a direct proportionality between CTE and evaporator pressure and an inverse proportionality between CTE and FFH pressure. The fluids R113 and R114 presented an opposite behavior with an inverse proportionality between the CTE and the evaporator pressure and between the CTE and the FFH pressure. Isentropic fluids presentes no pattern of behavior related to the CTE. For the subcritical cycle with superheating, we can see a direct proportionality between the CTE and the superheating process temperature and an inverse proportionality between the CTE and the feeding fluid heater (FFH) pressure. This behavior replicates itself for the wet and isentropic working fluids, except for the R123 fluid, which presented a very singular behavior. The dry fluids presented an almost complete dependency on FFH pressure, mainly for superheating dimensionless temperatures below 1.2. Another exception happened to the Isopentane fluid, which presented an inverse proportionality between CTE and superheating temperature and between CTE and FFH pressure. In the supercritical cycle, some particularities were identified for the CTE behavior, considering each working fluid used. Wet fluids presented a regular direct proportionality between the CTE and the supercritical temperature and an inverse proportionality between the CTE and the FFH pressure. R22 and R32 presented a greater dependency on the supercritical temperature, when compared to its relation with the FFH pressure, specially for FFH pressure values lower than 0.6. Isentropic and dry fluids presented a very particular behavior related to the CTE. R123 basically presented a CTE behavior that depends exclusively on the FFH pressure, with an inverse proportionality between the CTE and the FFH pressure. Isobutane, R113, R114, R11 and R245fa presented a cirect proportionality between the CTE and the supercritical temperature and an inverse proportionality between the CTE and the FFH pressure, however, a CTE greater dependency on the FFH pressure can be seen for all these fluids, specially for supercritical temperature above 1.3.

The development of graph representations is a great method for the understanding of the CTE behavior for each fluid and each fluid category within every thermodynamic cycle. Through these representations, it was possible to identify the cycle and fluids peculiarities in order to perform more assertive decisions about variable correlations later.

Figure 3

Cycle thermal efficiency (CTE) graph representation for the subcritical cycle with superheating.



RESULTS

Statistical Analysis (Correlation and Multiple Linear Regression)

The results of CTE allowed the development of a statistical analysis for each cycle and fluid category considered in this paper. Initially, the correlation between the CTE and the operating parameters was calculated. The resulting values denote the influence of each variable in CTE behavior, thus, the closer to 1, the stronger the correlation. The correlation results for each fluid category within each thermodynamic cycle can be seen in the Tab. 2.

Table 2

Correlation between cycle thermal efficiency (CTE) and operating parameters.

Operating Parameter	Subcritical			Subcritical with Superheating			Supercritical		
	Wet	Dry	Isentropic	Wet	Dry	Isentropic	Wet	Dry	Isentropic
T_{evap}	0.9938	0.9538	0.9507	0.9853	0.9567	0.6876	-	-	-
p_{evap}	0.3915	0.4627	-0.0048	-	-	-	-	-	-
T_{sup}	-	-	-	0.9987	0.9996	0.9995	-	-	-

T_{supc}	-	-	-	-	-	-	0.9946	0.9524	0.9402
Δ_T *	-	-	-	0.8139	0.7203	0.7189	-	-	-
p_{reg}	0.3493	0.1190	-0.1120	0.3547	0.1868	0.04015	0.3523	0.1845	0.0581

Through the analysis of the data available in Tab. 2, we can realize that the highest correlations regards to the evaporation (T_{evap}) temperature and CTE for the subcritical cycle, to the superheating temperature (T_{sup}) and the CTE for the superheated cycle and to the supercritical temperature (T_{supc}) and the CTE for the supercritical cycle. Then, through these results, multiple linear regression expressions were developed for each cycle, in order to express the CTE behavior according to the operating parameters with highest influence over the CTE and according to FFH pressure (p_{reg}), considered, in this study, a secondary variable of interest. The ajusted R-square is a variable that represents the joint influence of several operating parameters over the output variable. The estimated deviation denotes the standard error for the mathematical model.

The statistical analysis for the subcritical cycle showed a high correlation between the selected operating parameters and the CTE with a low values of estimated deviation. The wet fluids presented an adjusted R-square of 98.94% with an estimated deviation equal to 0.6752%. That is, 98.94% of the CTE behavior can be explained by the variables evaporation temperature (T_{evap}) and FFH pressure (p_{reg}), with an estimated deviation lower than 1%. For the dry fluids, the adjusted R-square value is 90.75% with an estimated deviation of 0.9498%. For the isentropic ones, 93.45% of the CTE behavior can be explained by the selected operating parameters, considering an estimated deviation equal to 0.9253%. TedfvccvThe expressions of CTE for the subcritical cycle can be seen in the Tab. 3.

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Table 3

Cycle thermal efficiency (CTE) multiple linear regression for subcritical cycle.

Subcritical	CTE multiple linear regression	Adjusted R-square	Estimated Deviation
Wet	$CTE = 4.146 + 0.101 T_{evap} + 0.0002 p_{reg}$	98.94%	0.6752%
Dry	$CTE = 9.186 + 0.096 T_{evap} - 0.0018 p_{reg}$	90.75%	0.9498%
Isentropic	$CTE = 7.193 + 0.084 T_{evap} - 0.00037 p_{reg}$	93.45%	0.9253%

For the superheated cycle, the statistical analysis also provided high values for the multiple linear regressions. For wet fluids, an adjusted R-square of 98.17% with an estimated deviation of 0.9628% was obtained, considering the explaining of the CTE behavior through the variables superheating temperature (T_{sup}) and FFH pressure (p_{reg}). For the dry fluids, an adjusted R-square of 80.77% with an estimated deviation of 1.2928% was calculated. Lastly, for the isentropic fluids, 89.77% of the CTE behavior can be explained by the operationg parameters considered for this cycle, with an estimated deviation equal to 1.1489%. The expressions of CTE for the subcritical cycle with superheating can be seen in the Tab. 4.

Table 4

Cycle thermal efficiency (CTE) multiple linear regression for subcritical cycle with superheating.

Superheated	CTE multiple linear regression	Adjusted R-square	Estimated Deviation
Wet	$CTE = 4.629 + 0.089T_{sup} + 0.00025p_{reg}$	98.17%	0.9628%
Dry	$CTE = 8.287 + 0.071T_{sup} + 0.00029p_{reg}$	80.77%	1.2928%
Isentropic	$CTE = 8.065 + 0.058T_{sup} + 0.00026p_{reg}$	89.77%	1.1489%

Supercritical cycle also presented high values for the adjusted R-square, with low values of estimated deviation. For the category wet fluids, 99.11% of the CTE behavior can be explained by the variables supercritical temperature (T_{supc}) and FFH pressure (p_{reg}), considering an estimated deviation equal to 0.7009%. Dry fluids presented an adjusted R-square of 90.43%. The estimated deviation for this category is 0.9541%. For the isentropic category, CTE behavior is explained through the same variables with a value equal to 87.86%, with an estimated deviation of 1.3603%. The expressions of CTE for the supercritical cycle can be seen in the Tab. 5.

Table 5

Cycle thermal efficiency (CTE) multiple linear regression for supercritical cycle.

Supercritical	CTE multiple linear regression	Adjusted R-square	Estimated Deviation
Wet	$CTE = 5.25 + 0.087T_{supc} + 0.00024p_{reg}$	99.11%	0.7009%
Dry	$CTE = 8.042 + 0.0764T_{supc} - 0.0001374p_{reg}$	90.43%	0.9541%
Isentropic	$CTE = 8.443 + 0.0614T_{supc} + 0.0003p_{reg}$	87.86%	1.3603%

COMPARISON BETWEEN MULTIPLE LINEAR REGRESSION CTE AND THERMODYNAMIC CTE

Through the multiple linear regression expressions previously listed, new calculations were performed in order to obtain CTE results for each working fluid within each thermodynamic cycle. Performing a comparison between the CTE results obtained through the multiple linear regression method and the CTE results obtained through the thermodynamic method, it was possible to evaluate the average deviation for each fluid category within each type of cycle (subcritical, subcritical with superheating and supercritical). Through the Tab. 6. It is possible to see the low values for CTE average deviation (all under 1%, except for the isentropic fluid category working in supercritical cycle). The wet fluid category presented the smallest CTE average deviation for all themodynamic cycles considered in this paper, with an overall average equal to 0.4133%. The dry fluid category presented an overall average worse than wet ones, with value equal to 0.7167%. Lastly, the isentropic fluids showed a low CTE average deviation, especially if we disregard the supercritical cycle, where the deviation presented the highest value for the category. Excluding this value, the isentropic category presented an overall average equal to 0.67%, a result very close to the obtained value for the dry fluids. However, considering the supercritical cycle result, the overall CTE deviation for this fluid category is 0.79%.

Table 6

Cycle thermal efficiency (CTE) average deviation by fluid category and thermodynamic cycle.

	Subcritical	Subcritical with Superheating	Supercritical
Wet	0.41	0.38	0.45
Dry	0.83	0.69	0.61
Isentropic	0.68	0.66	1.04

A subsequent comparison was also performed in order to evaluate the CTE average deviation for each working fluid within each thermodynamic and validate the method developed. The deviation consists in the difference between the CTE results obtained through the thermodynamic method and the results obtained through the multiple linear regression method, for each working fluid considered in this paper. Fig. 4 shows the average deviation results for the subcritical cycle. Fig. 5 regards to the subcritical cycle with superheating and Fig. 6 to the supercritical cycle.

Figure 4

Cycle thermal efficiency (CTE) average deviation by working fluid for the subcritical cycle.

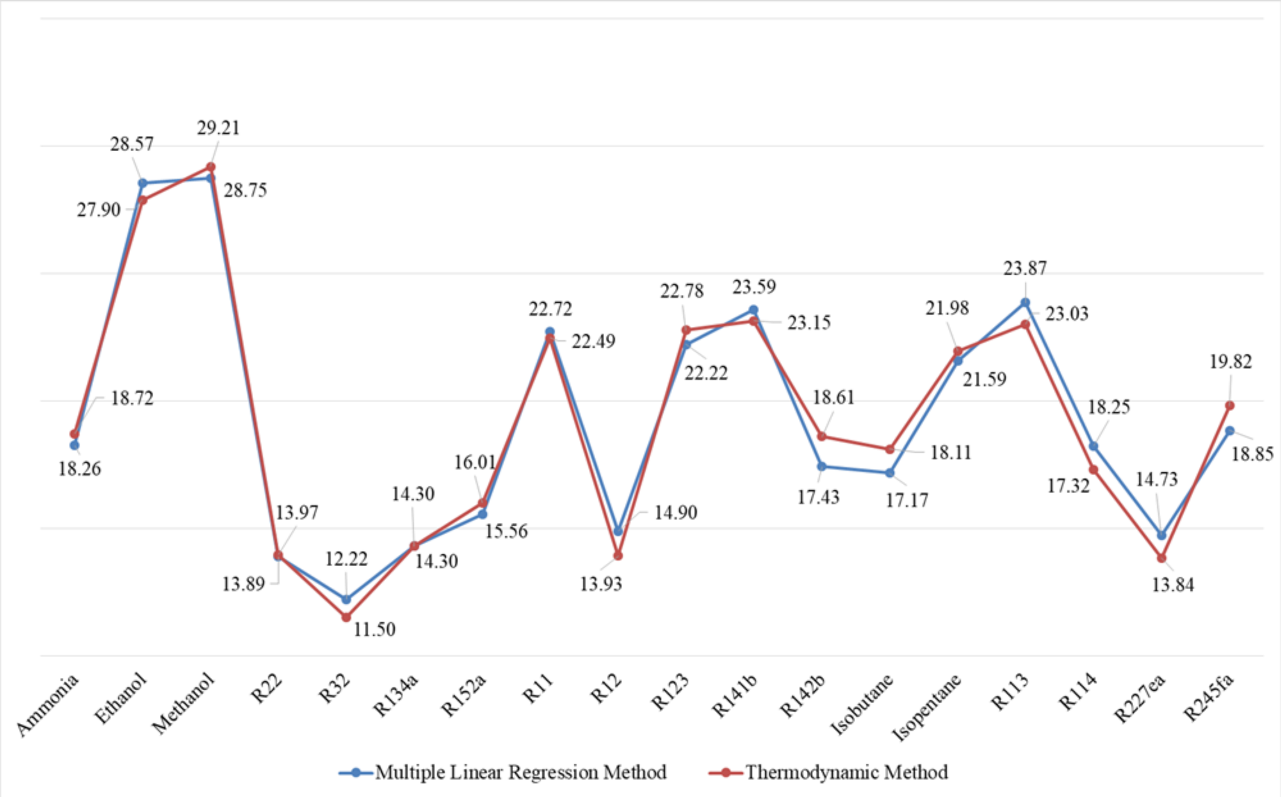


Figure 5

Cycle thermal efficiency (CTE) average deviation by working fluid for the subcritical cycle with superheating

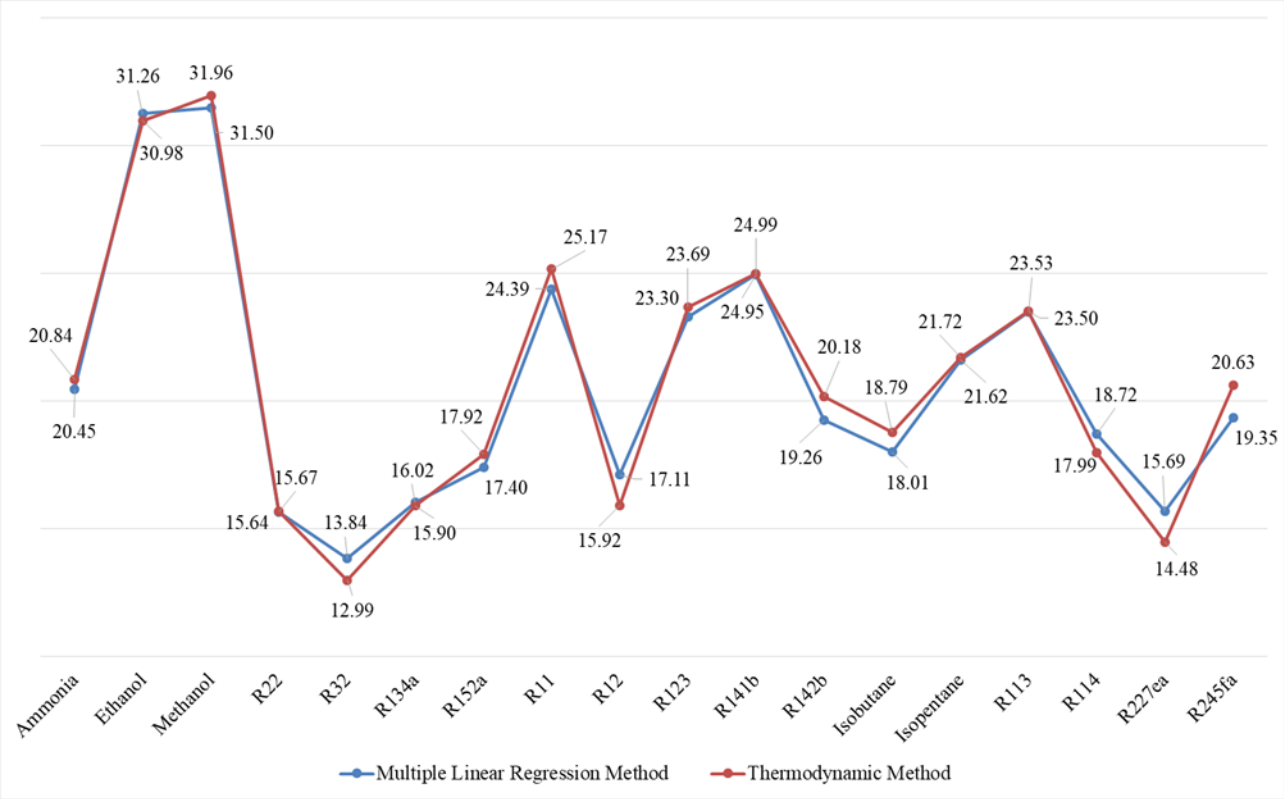
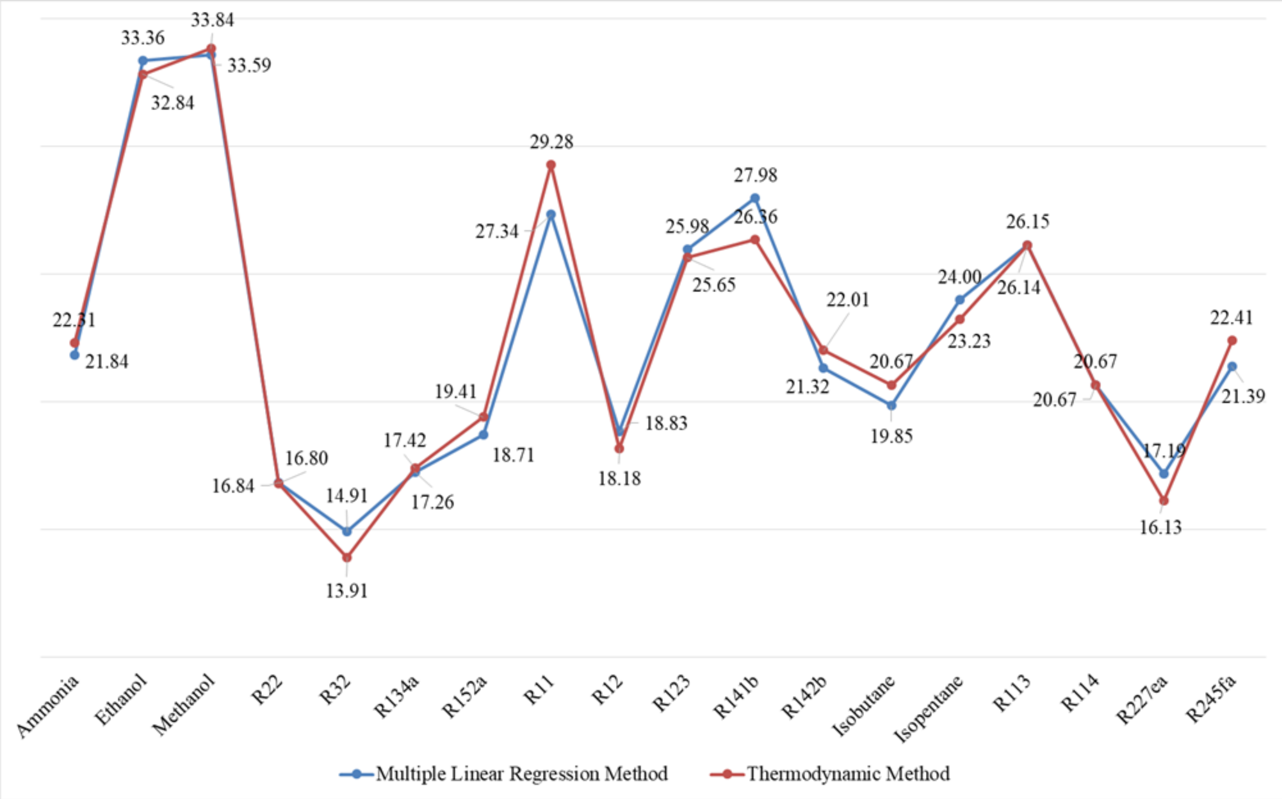


Figure 6

Cycle thermal efficiency (CTE) average deviation by working fluid for the supercritical cycle.



FLUID SELECTION

The validation for the fluid selection method regards to a comparison between the best CTE sequence produced by the thermodynamic method and the best CTE sequence produced by the multiple linear regression method (developed method). The CTEs considered for the comparison consist in the average CTE, that is, the averaging CTE's resultant of all range of input operating parameters for each working fluid. Fluid selection through the average CTE method for each thermodynamic cycle can be seen in Tab. 7.

Table 7

Cycle thermal efficiency (CTE) multiple linear regression for supercritical cycle.

Subcritical Cycle				Subcritical Cycle with Superheat			
Fluid	CTE_{aver} (%)	Fluid	CTE_{aver} (%)	Fluid	CTE_{aver} (%)	Fluid	CTE_{aver}
Methanol	29,21	Methanol	28,75	Methanol	31,96	Methanol	31,50
Ethanol	27,90	Ethanol	28,57	Ethanol	30,98	Ethanol	31,26
R141B	23,15	R113	23,87	R11	25,17	R141B	24,95
R113	23,03	R141B	23,59	R141B	24,99	R11	24,39

R123	22,78	R11	22,72	R123	23,69	R113	23,50
R11	22,49	R123	22,22	R113	23,53	R123	23,30
Isopentan	21,98	Isopentan	21,59	Isopentan	21,72	Isopentan	21,62
R245FA	19,82	R245FA	18,85	Ammonia	20,84	Ammoni	20,45
Ammonia	18,72	Ammonia	18,26	R245FA	20,63	R245FA	19,35
R142B	18,61	R114	18,25	R142B	20,18	R142B	19,26
Isobutane	18,11	R142B	17,43	Isobutane	18,79	R114	18,72
R114	17,32	Isobutane	17,17	R114	17,99	Isobutane	18,01
R152A	16,01	R152A	15,56	R152A	17,92	R152A	17,40
R134A	14,30	R12	14,90	R12	15,92	R12	17,11
R22	13,97	R227EA	14,73	R134A	15,90	R134A	16,02
R12	13,93	R134A	14,3	R22	15,67	R227EA	15,69
R227EA	13,84	R22	13,89	R227EA	14,48	R22	15,64
R32	11,50	R32	12,22	R32	12,99	R32	13,84

Supercritical Cycle			
Fluid	CTE_{aver} (%)	Fluid	CTE_{aver}
Methanol	33,84	Methanol	33,59
Ethanol	32,84	Ethanol	33,36
R11	29,28	R141B	27,98
R141b	26,36	R11	27,34
R113	26,14	R113	26,15
R123	25,65	R123	25,98
Isopentane	23,23	Isopentane	24
R245FA	22,41	Ammonia	21,84
Ammonia	22,31	R245FA	21,39
R142B	22,01	R142B	21,32
R114	20,67	R114	20,67
Isobutane	20,67	Isobutane	19,85
R152A	19,41	R12	18,83
R12	18,18	R152A	18,71
R134A	17,42	R134A	17,26
R22	16,8	R227EA	17,19
R227EA	16,13	R22	16,84
R32	13,91	R32	14,91

According to the data available in Tab. 7, there was practically no changes in CTE sequences, when comparing both methods (thermodynamic and multiple linear regression), with Methanol as the best working fluid in terms of CTE for all the thermodynamic cycles considered in this paper. For the subcritical cycle, some sequence inverses can be observed, however, a single CTE's difference greater than 1% can be seen in whole cycle, for the fluid R142b (1.18%). All the other fluid CTE's deviations are less than 1% and the CTE absolute mean error for the subcritical cycle is 0.621%. The smallest difference observed regards to the fluid R134a, with a null CTE deviation. For the subcritical cycle with superheating, the best CTE sequence resultant from the multiple linear regression method remains very close to the sequence produced by the thermodynamic method. For this cycle, we can observe three fluids with average CTE deviation greater than 1%: R245fa (1.28%), R12 (1.19%) and R227ea (1.21%). The smallest difference for this cycle regards to the fluids R22 and R113 (0.03% for both). The CTE absolute mean error for the superheated cycle is even smaller than the subcritical cycle, with value equal to 0.5711%).

Lastly, the supercritical cycle presented the highest CTE absolute mean error (0.6690%), however, this value is still very low. For this thermodynamic cycle, four fluids presented a CTE deviation greater than 1%: R141b (1.62%), R11 (1.94%), R245fa (1.02%) and R227ea (1.06%). The smallest CTE deviation for this cycle relates to the fluid R114m with a null difference. The average values obtained through calculations for each thermodynamic cycle meets, roughly, the estimated deviation provided by statistical analysis, previously performed, even with lower values. A comparison between the CTE estimated deviation and the CTE absolute mean error can be seen in Tab.8.

Table 8

Comparison between CTE estimated deviation and CTE absolute mean error.

	Subcritical			Subcritical with Superheating			Supercritical		
	Wet	Dry	Isentropic	Wet	Dry	Isentropic	Wet	Dry	Isentropic
CTE Estimated Deviation	0.6752%	0.9498%	0.9253%	0.9628%	1.2928%	1.1489%	0.7009 %	0.9541%	1.3603%
CTE Absolute Mean Error	0.4057%	0.8267%	0.6760%	0.4043%	0.6883%	0.6640%	0.4486 %	0.6133%	1.0460%

CONCLUSIONS

Multiple linear regression expressions can be developed in order to obtain CTE values from cycle operating parameters. However, a carefully evaluation must be performed in order to identify the variables with highest influence level over the CTE. Thus, a linear correlation shall be considered before the multiple linear regressions development. The results for linear correlation found very high values between CTE and evaporation temperature (T_{evap}) for the subcritical cycle (all over 95%), which denotes this is the most important variable related to CTE results for this thermodynamic cycle. The superheating temperature presented the highest linear correlation with CTE for the subcritical cycle with superheating. For all working fluid categories, the correlation results between CTE and superheating temperature are over 99,8%, which denotes a very high influence of the latter over the CTE. Lastly, for the supercritical cycle, the most significant operating parameter identified through linear correlation was the supercritical temperature, presenting values over 94% for all working fluid categories. Although the FFH pressure has not presented a high linear correlation value with the CTE, it was also considered as a secondary variable for multiple linear regression development, due to its influence over the CTE observed in graph analyze.

The results provided by the statistical data allow to affirm the validity of the developed method, with high adjusted R-square values (overall average of 94.38% for the subcritical, 89.57% for the superheated and 92.47% for the supercritical) and low estimated deviation values for the multiple linear regressions (average less than 1% for each working fluid category within each themodynamic cycle). Highest adjusted R-square values can be observed for the subcritical cycle (greater than 90% for each fluid category), specially for the wet fluids, with value greater than 98%. For the subcritical cycle with superheating, lower adjusted R-square results are observed when compared to the subcritical cycle, but still denotes high values. Wet fluids presented adjusted R-square greater than 98% once again for superheated cycle. Isentropic fluids presented a value close to 90%, and the worst result for this cycle regards to the dry fluids, with value around 81%. The supercritical cycle also presented high values for adjusted R-square. The wet fluids had the best results once again, with an adjusted R-square equal to 99%. The categories dry and isentropic presented values close to 90%.

Average CTE deviation presented low values for all working fluid categories within each thermodynamic cycle. Wet fluids presented average deviations from 0.38% (subcritical cycle) to 0.45% (supercritical cycle). Dry fluids presented an inverse behavior through the cycles, when compared to the subcritical cycle. This category had its worst (highest) CTE average deviation in subcritical cycle (0.83%) and its best (smallest) value for the supercritical cycle (0.61%). The category isentropic presented the worst result within all categories regarding to the supercritical cycle (1.04% of CTE average deviation). On the other hand, results close to the categories wet and dry can be seen for subcritical (0.68% of CTE average deviation) and for subcritical superheated cycle (0.66% of CTE average deviation).

The average CTE deviation for each working fluid, illustrated by the distance between the lines in Fig.5, Fig.6 and Fig.7 makes clear the accuracy of calculations obtained by the multiple linear regression. In addition, the calculation of the CTE absolute mean error provided values even smaller than the CTE estimated deviation provided earlier by the statistical analyze. Thus, a general absolute mean error (considering all working fluid categories and all thermodynamic cycles) equal to 0.6414% can be found, result that confirms the multiple linear regression method accuracy.

Lastly, the comparison between the both CTE lists also confirms the validity of the developed method, due to its similar working fluids sequence. Few fluid inversions can be seen comparing the best CTE sequence obtained through the thermodynamic method and the best CTE sequence obtained through the multiple linear regression method, with CTE differences practically negligible.

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