U.P.B. Sci. Bull., Series D, Vol. 85, Iss. 2, 2023 ISSN 1454-2358

NEW POLYNOMIAL CORRELATIONS FOR THE OPTIMAL DESIGN OF THE PLATE-FIN HEAT EXCHANHGER USED IN GAS TURBINES

Traian TIPA[1], Daniel-Eugeniu CRUNȚEANU[2], Andrei-George TOTU[3], Andreea-Cătălina TOTU[4]

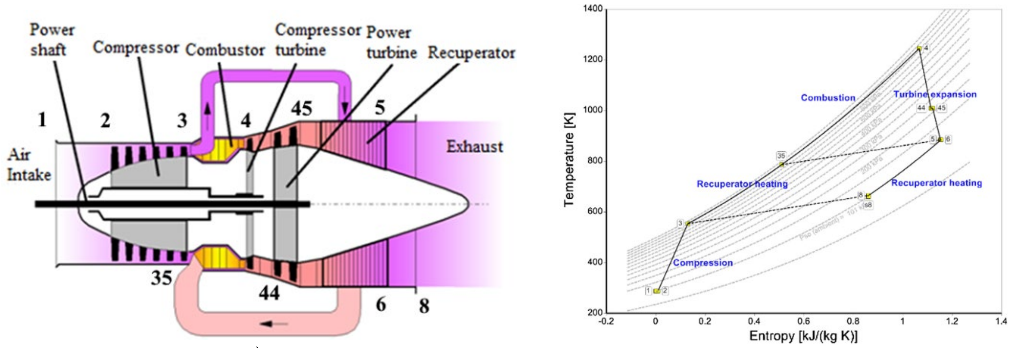
Nowadays, environmental concerns have attracted worldwide public attention after scientists gave proof of global warming. Therefore, there are some requirements even in gas turbine manufacturing to produce environment-friendly gas-turbine engines with lower emissions and higher specific fuel consumption (SFC) ratings. Those requirements can be met by incorporating heat exchangers into gas turbines. Relevant research in such areas as the design of a heat exchanger has been reviewed in this paper. Based on the mathematical calculations developed in this paper, different variations of the main heat exchanger's parameters are presented. Also, in the calculation process of any engineering component that uses a more or less documented working fluid, there is a need to know the variation of its thermodynamic properties. The present paper aims to define such variations, in linear or polynomial form, in order to be integrated into iterative calculation programs/codes.

Keywords: gas turbine, heat exchanger, thermodynamic parameter, linear regression, air properties, polynomial data.

1. Introduction

As it is known, a lot of power is required for operating jets and helicopters but also for electrical power generation and industrial applications, which is fulfilled by gas turbines. Over the past several decades, environmental issues received important attention leading to the growth of demand for environmentally friendly engines with lower emissions and improved specific consumption. These requirements can be met by incorporating heat exchangers into gas turbines, which leads to an increased gas-turbine cycle efficiency by transferring the heat from the hot burnt gases to compressed air before entering the combustion chamber (see fig.1) [1].

[1] Eng., National R&D Institute for Gas Turbines Comoti, Romania, e-mail: traian.tipa@comoti.ro
[2] Prof., University POLITEHNICA of Bucharest, Romania, e-mail: daniel.crunteanu@upb.ro
[3] Eng., National R&D Institute for Gas Turbines Comoti, Romania, e-mail: andrei.totu@comoti.ro
[4] Eng., National R&D Institute for Gas Turbines, Romania, e-mail: andreea.dobre@comoti.ro



a) b)

Fig.1 a). Illustration of a recuperated turboshaft engine; b). T-s diagram for the recuperated cycle based on GasTurb13 [2]

A heat exchanger is a heat transfer device that is used for the transfer of internal thermal energy between two or more fluids available at different temperatures. In most heat exchangers, the fluids are separated by a heat transfer surface, and ideally, they do not mix [3]. Initial heat exchangers, that have been used in gas turbine systems, were essentially designed based on size limitation, reliability, and costs [4]. They are usually of three types according to their heat transfer surface geometry, such as primary surface, plate-fin, and tubular recuperators.

- Primary surface heat exchangers

The primary surface heat exchangers comprise thin corrugated sheets stacked together with gas (hot) stream and air (cold) stream flowing through alternate layers.

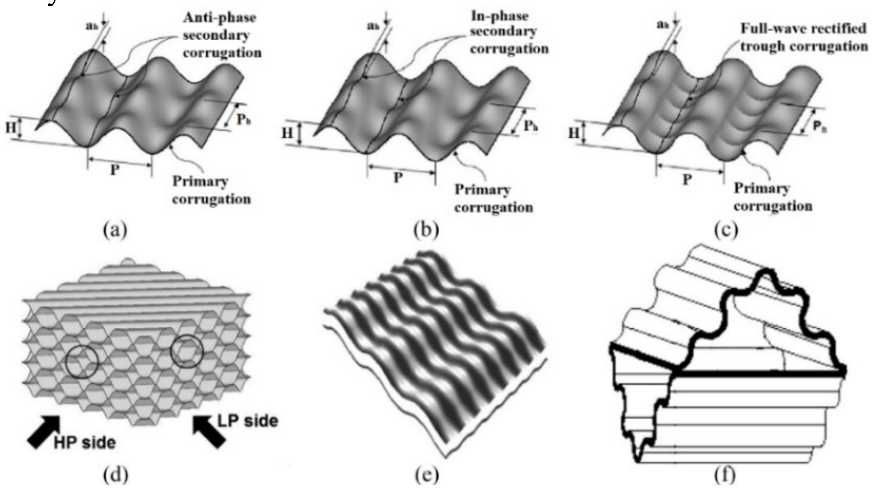


Fig. 2 Configurations of modified primary surfaces [5]

The main characteristic of this kind of construction is that heat transfer takes place directly through these thin plates without secondary surface fin efficiency effects. The primary surface heat exchanger is suitable for relatively low pressure

(LP) ratio engine applications, like many turboshafts engines (≈15 bar). Recently, unlike traditional periodic profiles with simple geometry construction, some novel primary surfaces, having more complex 3D cross-corrugated geometries are shown in Fig.2.

Primary surface heat exchangers have been developed by many companies since the 1970s. Fig. 3 reveals various important types of recuperators, with different configurations and types of flow, counterflow, crossflow, parallel flow.

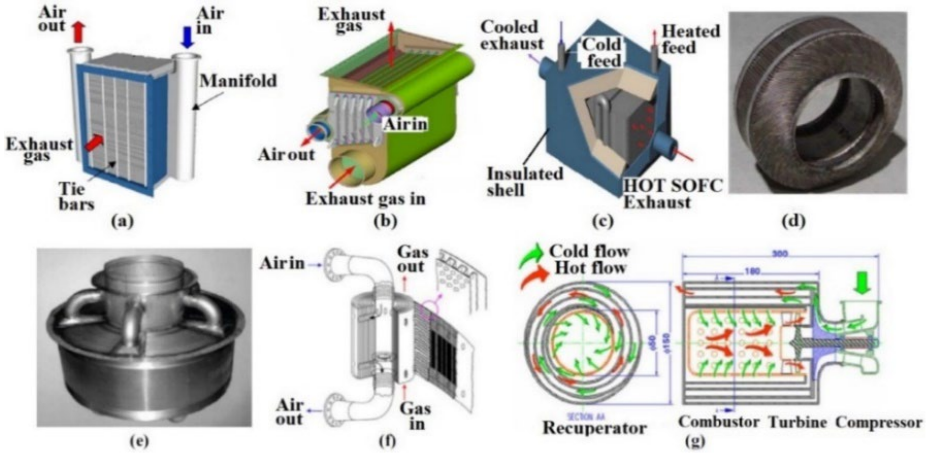


Fig.3 Pictures of recuperators from: a) RSAB [6]; b) Honeywell [7]; c) SIC [8]; d) Capstone [9]; e) ACTE [10]; f) Rolls-Royce [11]; g) Swiss-Roll [12]

- Plate-fin recuperators

Plate-fin recuperators mainly consist of a series of fin surfaces together with flat separators known as parting sheets. The main attribute of the plate-fin surface is that the introduced fins work as a secondary heat transfer surface and provide mechanical support against internal pressure differentials between layers. Ingersoll-Rand began to develop plate-fin recuperators, which adopt offset fins in the heat exchange area, as shown in Fig.4 [13]. AlliedSignal produced an industrial gas-turbine plate-fin recuperator with offset plate-fin surfaces, and the entire heat exchanger (plate, fins, header bars, and manifolds) was brazed to form a very strong monolithic unit [14]. Abiko invented a plate-fin heat exchanger for micro gas turbines with four different embodiments of their invention [15].

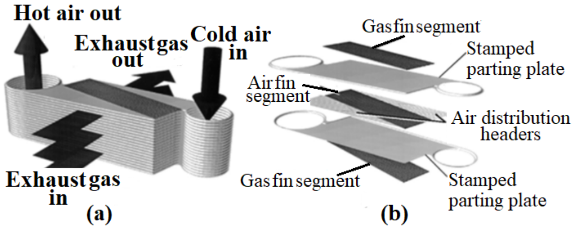


Fig.4 Flow paths (a) and a unit cell (b) of an Ingersoll-Rand's plate-fin recuperator [13]

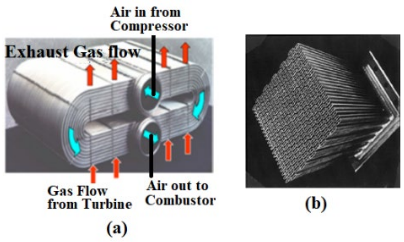


Fig. 5 MTU tubular recuperator: (a) Fluids flow; (b) Cross-section [13]

- Tubular recuperators

Tubular recuperators consist of a series of tubes within an outer shell. As shown in Fig.5, MTU developed a cross-counter flow recuperator that consisted of two manifold tubes and a bundle of profile tubes.

Regarding heat exchanger design it can be said that it is an iterative complex process and involves a series of major considerations regarding thermal, hydraulic, and mechanical calculations, and other specific aspects as it is shown in Fig.6. To start the thermal and hydraulic calculations of the heat exchanger, a series of theoretical aspects must be established. First, the problem specification must be defined, which involves the process parameters, operating conditions, and environment in which the heat exchanger is going to be operated [16]. Based on the problem specifications it is established the construction type of the heat exchanger, the flow arrangement, surface selection, size and shape consideration (geometrical parameters), and limitations. Thus, in the first part of this paper, it is shown the influence of geometric parameters on heat exchangers' performances to obtain the optimal geometric parameters.

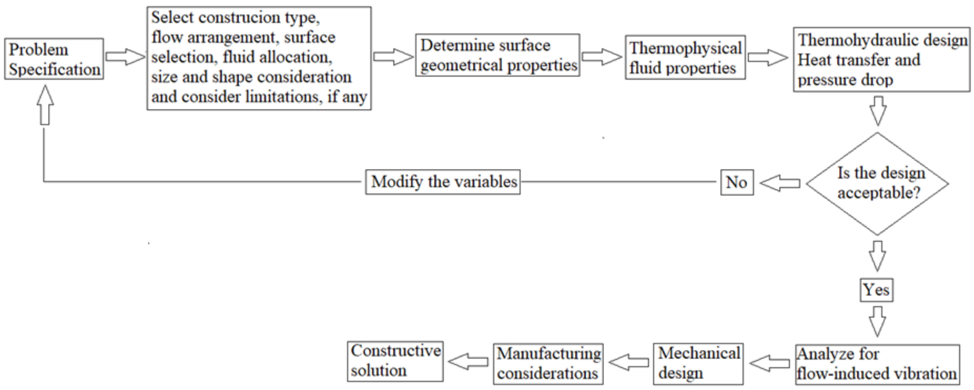


Fig.6 Heat exchanger design steps

Once these constructive considerations are established, the next step in the heat exchanger design process is to identify the fluids thermophysical properties needed for heat transfer and pressure-drop analysis such as the following: thermal conductivity, kinematic viscosity, specific isobar heat capacity, thermal diffusivity, and density. As it is known, these properties vary with fluids' temperature and pressure. When heat transfer and pressure-drop calculations are made, these properties need to be chosen from the tables, and this process takes a lot of time. This paper offers a solution to optimize the heat exchanger design process by introducing formulas for these properties. The formulas could be used in other applications, within the presented limits. The data used to obtain the polynomial coefficients are chosen arbitrarily, at the scientific level there are several sources from which to start.

2. Choosing the optimal heat exchanger's geometric parameters

In order to obtain a high-performance constructive solution for a plate-fin heat exchanger (in this case), with the desired performances imposed in the design theme, the influence of the geometric parameters and the main parameters that characterize the heat exchanger's performance must always be taken into consideration. The main geometric parameters wich define the flow channels of a plate-fin heat exchanger are the distances Dpl_1, Dpl_2 between plates (fin hights) and the fin pitch p_1,p_2 (see Fig. 7).

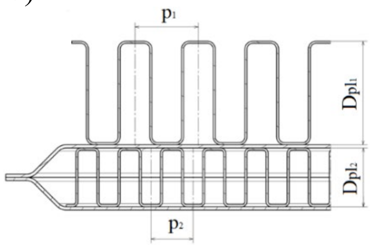


Fig.7 Main plate-fin heat exchanger's geometric parameters

Thus, for different pitch, the distances between the plates were varied, and for a constant flow rate of the working fluids, the influence of these parameters on the flow velocities was analyzed (see Fig.8, Fig.9). For an efficient heat transfer and low pressure drop, the optimal flow velocities of the working fluids through the heat exchanger's channels are a maximum of ~30m/s for the primary fluid (exhaust gas) and ~10m/s for the secondary fluid (compressed air) [3].

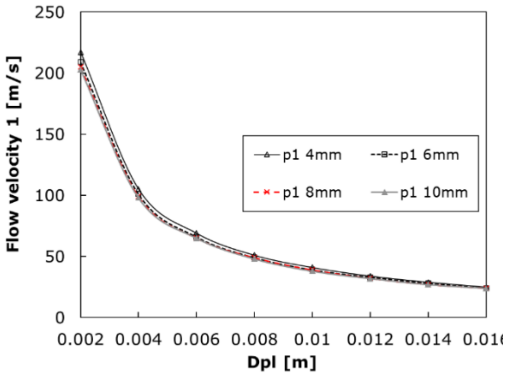


Fig. 8 The geometric parameters' influence on primary fluid's flow velocity

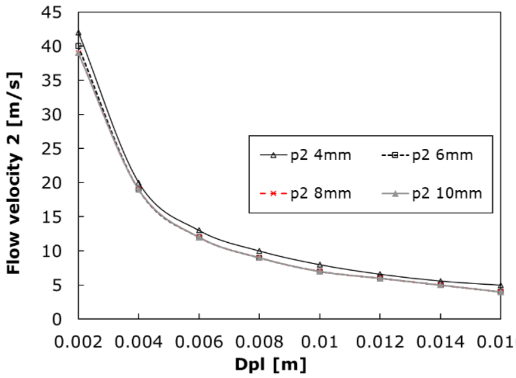
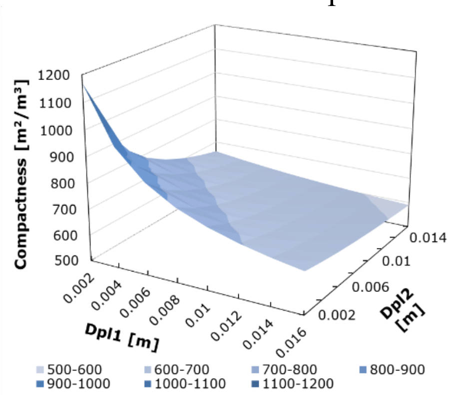


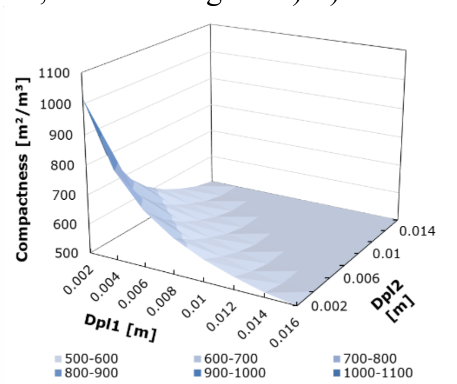
Fig. 9 The geometric parameters' influence on secondary fluid's flow velocity

Thus, the flow velocities with values close to the above are followed in choosing the optimal geometric parameters for the heat exchanger surface. Analyzing the graphs obtained (Fig.8 and 9), the variation of the corrugation pitch does not have a considerable influence on the flow velocities, and they have values close to the optimal ones for distances between plates of more than 10 mm for the primary fluid and 6 mm for the secondary fluid.

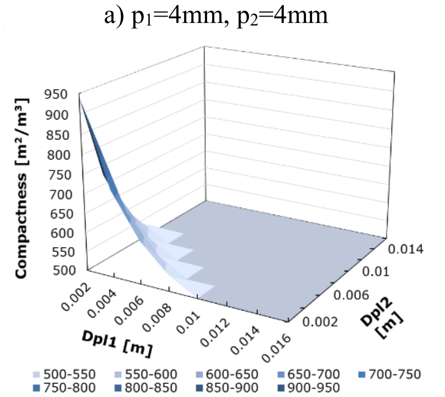
Another important parameter that defines a high-performance heat exchanger is its compactness defined as the ratio between the total heat exchange surface and the volume that it occupies. The heat exchanger is considered compact for values over 700 m^2/m^3 on at least one of the fluid parts [17]. The influence of the geometrical parameters on the compactness of the heat exchanger was analyzed in the calculation model developed for different variation configurations, shown in Fig. 10 and 11. The distances between the plates varied from 2 to 16 mm for different values of the fins' pitch of 4 to 10 mm, shown in Fig. 10.a)-d).



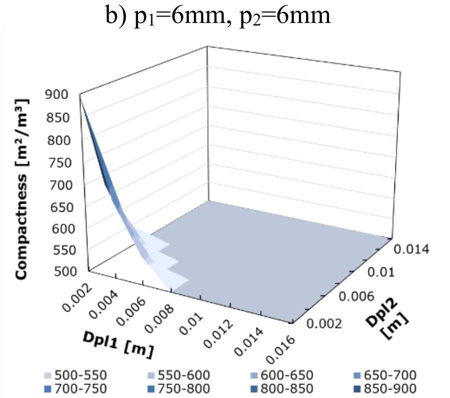
a) p_1=4mm, p_2=4mm



b) p_1=6mm, p_2=6mm



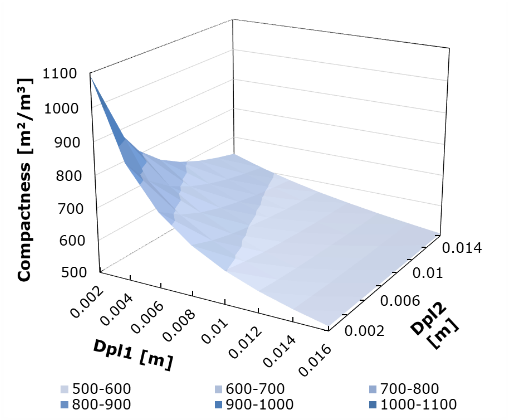
c) p_1=8mm, p_2=8mm



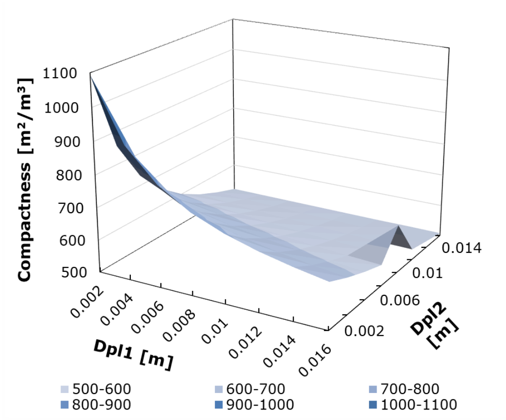
d) p_1=10mm, p_2=10mm

Fig. 10 The geometric parameters' influence on heat exchanger's compactness

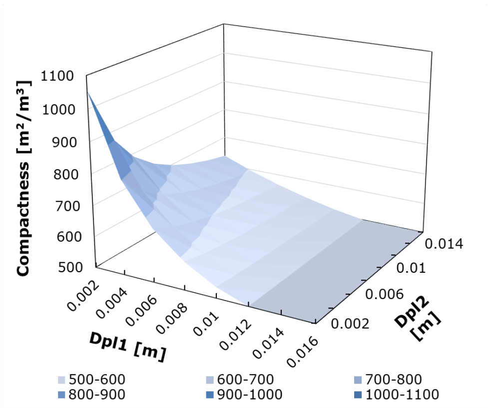
Analyzing the graphs obtained, for small values of plate's distances at different pitches, the heat exchanger's compactness has the desired values over 700 m^2/m^3. In Fig. 11. a)-f), also for the same variation of plate spacing values from 2 to 16 mm, the corrugation pitches for the two flow channels were alternately varied to observe the influence on compactness.



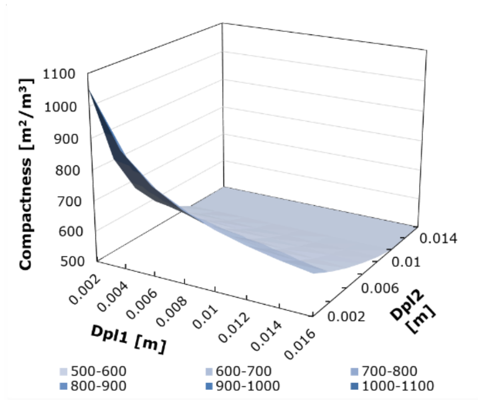
a) p_1=4mm, p_2=6mm



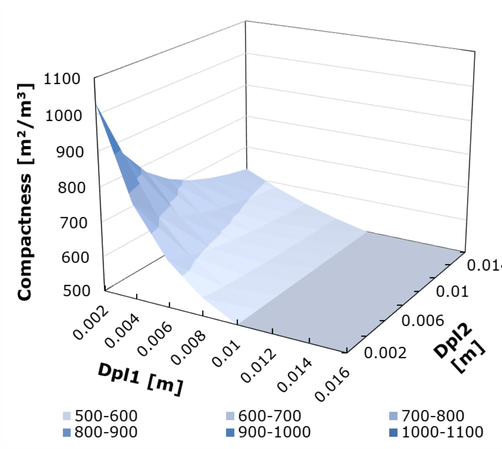
b) p_1=6mm, p_2=4mm



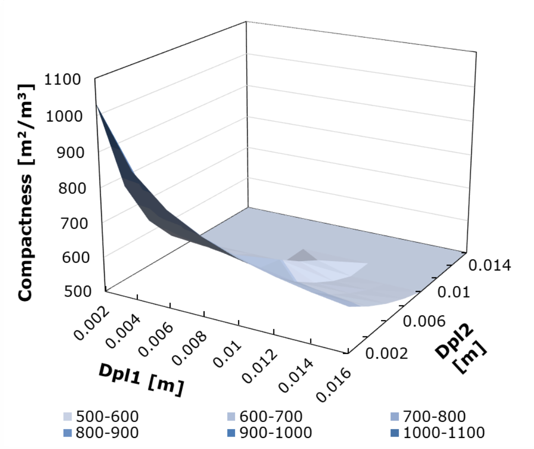
c) p_1=4mm, p_2=8mm



d) p_1=8mm, p_2=4mm



e) p_1=4mm, p_2=10mm



f) p_1=10mm, p_2=4mm

Fig. 11 The geometric parameters' influence on heat exchanger's compactness

To choose the optimal geometric parameters, the variation of the compactness comes in parallel with the variation of flow velocities through the channels. As the working fluids, exhaust gas, and compressed air have different densities, it is necessary to differentiate the flow front surfaces so that the velocities of the two fluids have values as close as possible to the optimal flow through the heat exchangers, of 10÷30m/s, to give sufficient time to the heat transfer by convection between the heat recovery walls and the working fluids and keep/maintain pressure losses as low as possible.

3. A numerical approach for fluid's thermophysical properties in heat exchanger design process

The concept of linear regression was originally introduced by Sir Francis Galton in the late 19th century. Linear regression is a statistical approach to a data set to define and quantify the relationship between the considered variables so that an interdependence law can be written [18]. This method is used successfully for various purposes, starting with statistics at the educational level [19], environmental issues [20], or economics [21]. Linear regression can be written in the simplest form according to relation (1), so that the result of this procedure will be a line defining the parameter **y** in relation to the variable **x** [22].

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{1}$$

Thing can be developed so that linear regression can consider several independent parameters [23], according to equation (2).

$$\boldsymbol{y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \dots + \beta_n x_n + \varepsilon} \tag{2}$$

The above relations are the basis of the linear approach. However, there are situations in which the variation of the parameters, no matter how limited the field of applicability, cannot be expressed by this type of law. A mathematical juggling can be done, by transforming an $\boldsymbol{\beta_1 x}$ element into $\boldsymbol{(\beta_1, x)x}$ and rewriting the relation (2) to reach a polynomial writing (polynomial regression). This new formula can be written according to relation (3), and the exemplification of its applicability can be deduced from Fig.12.

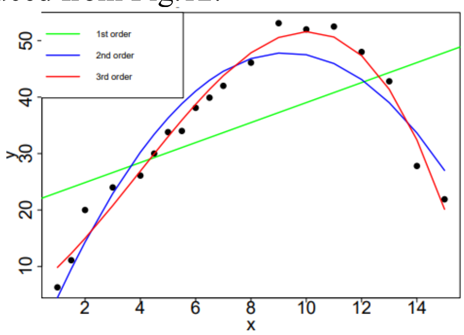


Fig. 12 Data fit using regressions of different orders [24]

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 + \beta_3 x_2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 +..+\beta_n x_n^m ... + \varepsilon \qquad (3)$$

Mathematical analysis on the extension of the linear regression method from a single independent variable to five such variables is presented in detail by Kurzmak [25]. For the current analysis, the mathematical formulation for obtaining the coefficients in the case of two independent variables can be written according to relations (4) - (5) [25] (in matrix form) where the following particularization is made: the 3rd, 4th and 5th independent variables to be in fact also the first two but in another form (quadratic or as a product). A linear regression model with multiple independent variables in a quadratic form was described by Wang et al. [26] which uses a normalization function.

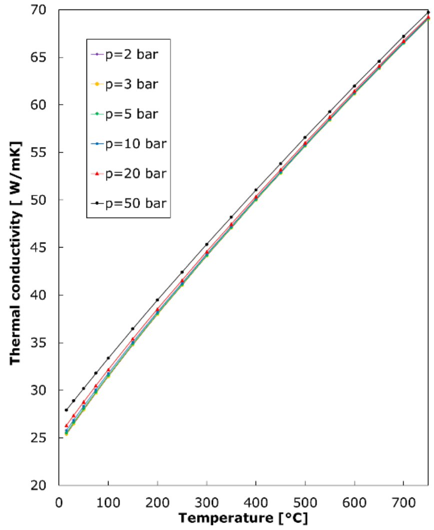
$$\begin{bmatrix} S_{X1Y} \\ S_{X2Y} \\ S_{X3Y} \\ S_{X4Y} \\ S_{X5Y} \end{bmatrix} = \begin{bmatrix} S_{x1x1} & S_{x1x2} & S_{x1x3} & S_{x1x4} & S_{x1x5} \\ S_{x2x1} & S_{x2x2} & S_{x2x3} & S_{x2x4} & S_{x2x5} \\ S_{x3x1} & S_{x3x2} & S_{x3x3} & S_{x3x4} & S_{x3x5} \\ S_{x4x1} & S_{x4x2} & S_{x4x3} & S_{x4x4} & S_{x4x5} \\ S_{x5x1} & S_{x5x2} & S_{x5x3} & S_{x5x4} & S_{x5x5} \end{bmatrix} \begin{bmatrix} \widehat{\beta_1} \\ \widehat{\beta_2} \\ \widehat{\beta_3} \\ \widehat{\beta_4} \\ \widehat{\beta_5} \end{bmatrix} \qquad (4)$$

$$\widehat{\beta_0} = \overline{Y} - \widehat{\beta_1}\overline{X_1} - \widehat{\beta_2}\overline{X_2} - \widehat{\beta_3}\overline{X_3} - \widehat{\beta_4}\overline{X_4} - \widehat{\beta_5}\overline{X_5} \qquad (5)$$

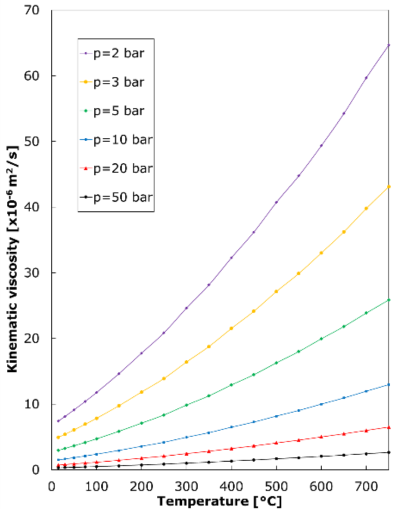
In relation (4) S represents a term used in the process of minimizing the SSE (Sum Squared Error) and is written in the general form using relation (6), $\overline{Y}$ is a dependent function, f = f (p, T, p^2, T^2, pT) in relation 5 and X_1 ... X_5 are the independent variables.

$$S_{XY} = \sum_{i=1}^{N} X_i Y_i - \left(\sum_{i=1}^{N} X_i\right)\left(\sum_{i=1}^{N} X_i\right)/N \qquad (6)$$

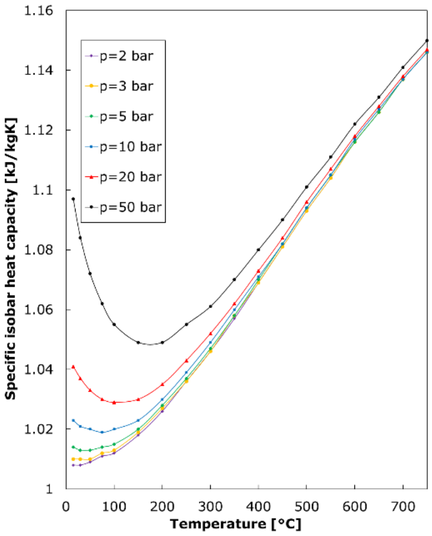
In order to appreciate the quality of the results obtained using the previously described mathematical procedure, one can deduce the so-called R^2 value which represents a statistical value that estimates how close the initial data are to the ones obtained by using the law above. As a mathematical relation, in [22] this R^2 value is defined as the ratio between the explained variation and total variation. R^2 can take values between 0 and 1 (0 and 100%), value 1 (100%) representing that the determined polynomial leads to obtaining data identical to those initially used. In general, the closer this parameter is to the value 1, the more accurate the applied method is. In the statistical interpretation, the so-called analysis of variance (ANOVA) can also be done, but it is more suitable for data that can be grouped into certain categories. Some 95% confidence intervals (CI) of the variables can be drawn, as Ira et al. [27] did in their paper. For the present analysis, the initial data to start with are obtained with the online program available in [22].



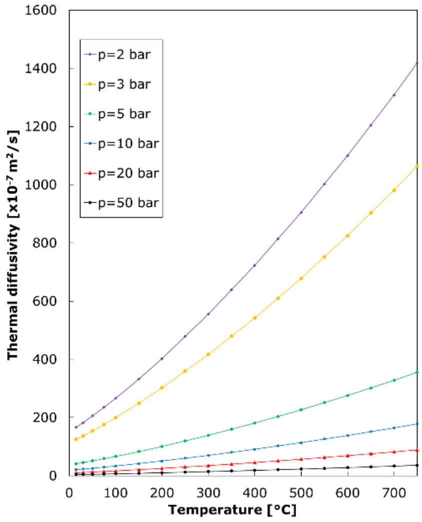
a) Thermal conductivity



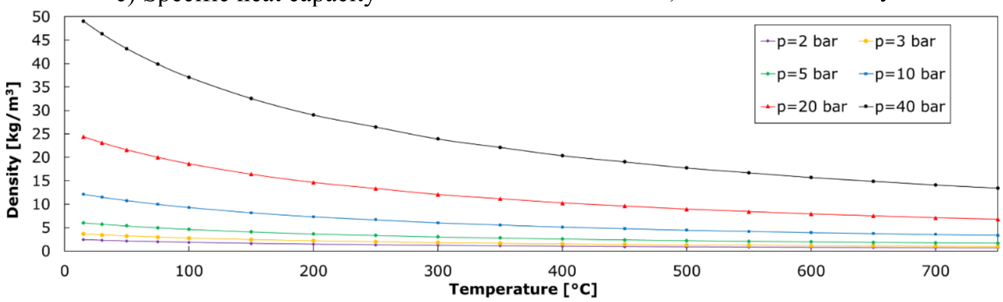
b) Kinematic viscosity



c) Specific heat capacity



d) Thermal diffusivity



e) Density

Fig. 13. Variation of main parameters

4. Polynomial results for fluid's thermophysical properties in heat exchanger design process

The linear regression model available in Microsoft Excel software was used for the calculation, a method successfully used by other authors [17] [20]. It was intended that the error obtained over a certain range of temperatures or pressures to be in the range of ± 3% (relative to the initial data). For these reasons, as seen in Tables 1-8 there is a multitude of polynomials for each analyzed parameter so that the final result is as accurate as possible. The results presented in the tables contain the coefficients of the resulting polynomials, which can have the linear form in relation (7) or the quadratic form in relation (8).

$$(p,T) = c_1^{lin} + c_2^{lin} \cdot T + c_3^{lin} \cdot p \quad (7)$$

$$f(p,T) = c_1 + c_2 \cdot T + c_3 \cdot p + c_4 \cdot p^2 + c_5 \cdot T^2 + c_6 \cdot p \cdot T \quad (8)$$

Table 1

Values of polynomial coefficients for density variation (temperature over 200°C)

Density [kg/m³]						
Pres. range [bar]	2-3	3-5	5-10	10-14	14-22	22-40
Temp. range [°C]	200-750	200-700	200-700	200-750	200-750	200-700
Max error* [%]	2.77	2.84	2.6	2.5	2.9	2.93
Avg. error* [%]	1.24	1.22	1.31	1.05	1.14	1.22
c_1	0.3982066	0.6684148	1.22648	1.982703	2.839097	4.826486
c_2	-0.001876	-0.0032247	-0.00596	-0.00961	-0.013738	-0.023299
c_3	0.80931876	0.8176638	0.821269	0.819856	0.819399	0.817217
c_4	0.00194791	0.00033296	-0.00018	-0.00014	-0.000169	-0.000187
c_5	1.9672E-06	3.39086E-06	6.27E-06	1.01E-05	1.44196E-05	2.4405E-05
c_6	-0.000687	-0.00069003	-0.00069	-0.00069	-0.000685	-0.000679

* compared to all known values in Peacesoftware [24], valid for all tables presented

Table 2

Values of polynomial coefficients for density variation (temperature below 200°C)

Density [kg/m³]			
P. range [bar]	2-7	7-20	20-50
T. range [°C]	15-200	15-200	15-200
Max error [%]	1.71	2.72	2.09
Avg. error [%]	0.89	0.75	0.81
c_1	0.176399	0.540282	1.337892
c_2	-0.00531	-0.01641	-0.04218
c_3	1.218073	1.221386	1.232196

Table 3

Values of polynomial coefficients for thermal conductivity variation

Thermal conductivity [x10⁻³ W/mK]		
P. range [bar]	2-50	2-50
T. range [°C]	75-750	15-75
Max error [%]	1.94	0.67

c_4	0.000101	5.92E-05	-5.8E-05
c_5	2.52E-05	7.81E-05	0.000204
c_6	-0.00258	-0.00262	-0.00271

Avg. error [%]	0.883	0.195
c_1^{lin}	25.8484	24.42086
c_2^{lin}	0.02898	0.0469
c_3^{lin}	0.05827	0.06769

Table 4

Values of polynomial coefficients for specific isobar heat capacity

Specific isobar heat capacity [kJ/kgK]			
Pres. range [bar]	2-50	2-25	25-40
Temp. range [°C]	75-750	15-750	15-750
Max error [%]	1.54 (p<20bar), 3.03(p>20bar)	2.66	3.68
Avg. error [%]	0.68 (p<20bar), 1.48 (p>20bar), 1.17 (2-50bar)	0.76	1.68
c_1^{lin}	0.999372193	0.999372	1.019892
c_2^{lin}	0.000842307	0.000842	0.000357
c_3^{lin}	0.000171745	0.000172	0.00017

Table 5

Values of polynomial coefficients for kinematic viscosity (pressure between 2-9bar)

Kinematic viscosity [x10^{-6} m^2/s]					
Pressure range [bar]	2-3	3-4	4-5	5-7	7-9
Temperature range [°C]	75-750	75-750	75-750	75-750	50-750
Max error [%]	2.52	2.13	1.944	3.94	2.46
Avg. error [%]	1.09	0.75	0.59	1.04	0.73
c_1	7.115961	4.9513	3.811264624	13.4734	10.04571
c_2	0.103559	0.072585	0.056026512	0.042664	0.031716
c_3	0	0	0	-3.59937	-1.99981
c_4	-0.24795	-0.08837	-0.04129123	0.2825	0.117778
c_5	3.28E-05	2.3E-05	1.77292E-05	1.34E-05	9.94E-06
c_6	-0.02542	-0.01272	-0.00763248	-0.00438	-0.00244

Table 6

Values of polynomial coefficients for kinematic viscosity (pressure between 9-40bar)

Kinematic viscosity [x10^{-6} m^2/s]					
Pressure range [bar]	9-12	12-15	15-20	20-30	30-40
Temperature range [°C]	75-750	15-750	15-750	75-750	15-750
Max error [%]	3.68	2.59	3.66	3.24	2.56
Avg. error [%]	0.78	0.58	0.67	0.94	0.61
c_1	7.719661	5.6652	4.62065	3.267307	2.29005
c_2	0.024202	0.018749	0.014534	0.010314	0.007265
c_3	-1.17324	-0.656435	-0.41983	-0.20969	-0.1036
c_4	0.05263	0.022777778	0.011281	0.003955	0.00139
c_5	7.581E-06	5.830E-06	4.52E-06	3.18E-06	2.24E-06
c_6	-0.00141	-0.0008503	-0.00051	-0.00025	-0.00013

Table 7

Values of polynomial coefficients for thermal diffusivity (pressure between 2-10bar)

Thermal diffusivity [x10^{-7} m^2/s]					
Pressure range [bar]	2-3	3-4	4-5	5-8	8-10
Temperature range [°C]	50-750	50-750	50-750	50-750	50-750
Max error [%]	1.77	2.42	3.39	2.29	2.18

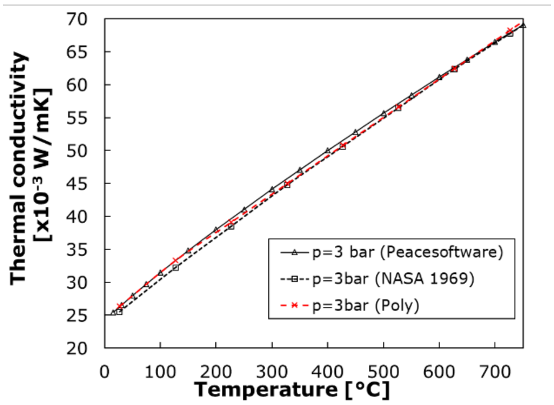
Avg. error [%]	0.68	0.92	1.49	0.66	0.67
c_1	157.1829	131.8889	106.2622	45.85838	42.50265
c_2	2.058526	2.191093	2.325263	0.519294	0.552476
c_3	0	0	0	-2.30237	-2.30793
c_4	-4.57735	-3.26994	-2.51066	0.000833	0.001111
c_5	0.000638	0.000456	0.000274	0.000154	0.000108
c_6	-0.4201	-0.4201	-0.42062	-0.042	-0.042

Table 8

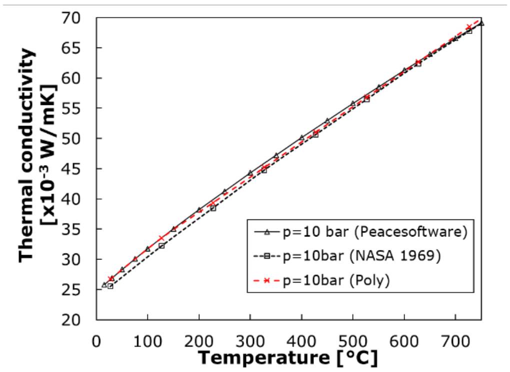
Values of polynomial coefficients for thermal diffusivity (pressure between 10-40bar)

Thermal diffusivity [x10^{-7} m^2/s]				
Pressure range [bar]	10-15	15-20	20-30	30-40
Temperature range [°C]	50-750	50-750	50-750	50-750
Max error [%]	2.24	2.5	2.61	2.23
Avg. error [%]	0.51	0.63	0.59	0.45
c_1	23.1404	21.44807009	12.37058	8.697672
c_2	0.258983	0.275532699	0.149292	0.10504
c_3	-0.58486	-0.581605838	-0.19398	-0.09931
c_4	0.000466	0.000277778	7.12E-05	5.96E-05
c_5	7.88E-05	5.59893E-05	3.7E-05	2.56E-05
c_6	-0.0105	-0.010501463	-0.0035	-0.00175

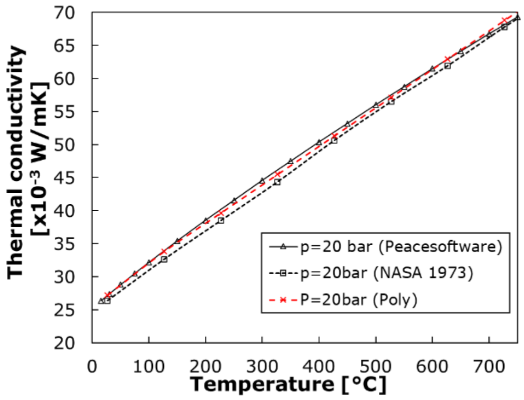
In Fig. 14 a)-o) are presented comparatively, for several values of pressure, the initial data together with the data obtained using the resulting polynomials. Other sources have been identified for validating both the correctness of the initial data and the resulting polynomials. Data from NASA technical reports [28] and AEDC [29], as well as scientific articles [30] or online helpers [31] were used. The resulting data for kinematic viscosity were compared with kinematic viscosity obtained by dividing by density the dynamic viscosity resulting from Sutherland's law [32].



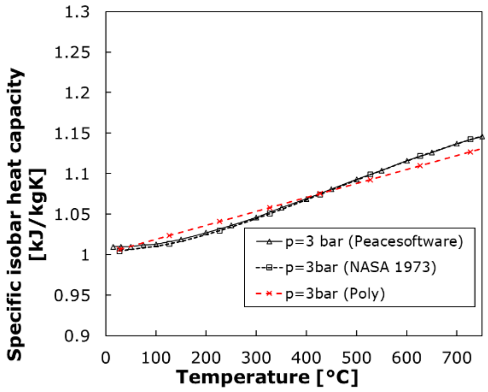
a) Thermal conductivity (p=3bar)



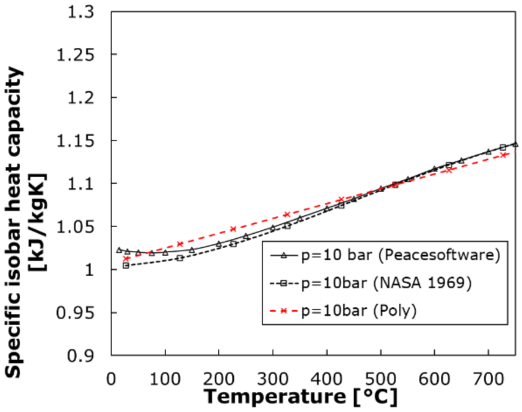
b) Thermal conductivity (p=10bar)



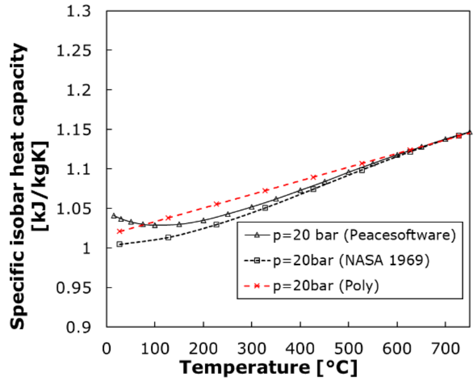
c)Thermal conductivity (p=20bar)



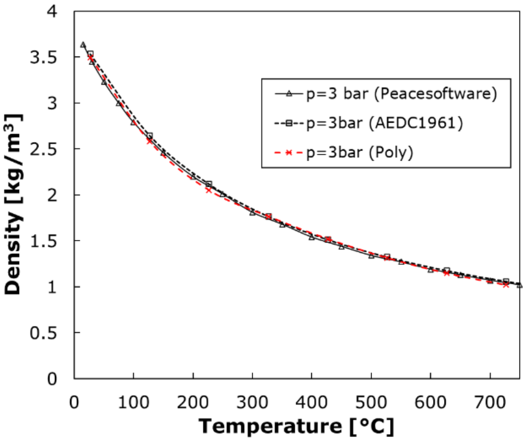
d) Specific heat capacity (p=3bar)



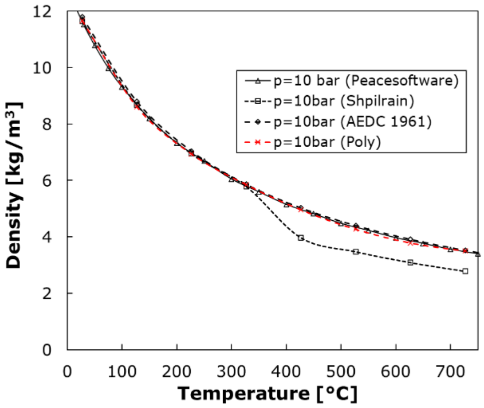
e) Specific heat capacity (p=10bar)



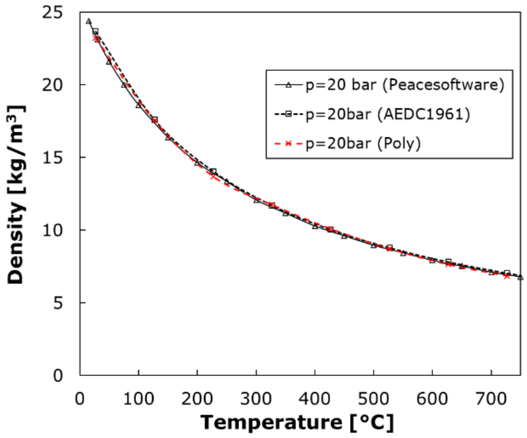
f) Specific heat capacity (p=20bar)



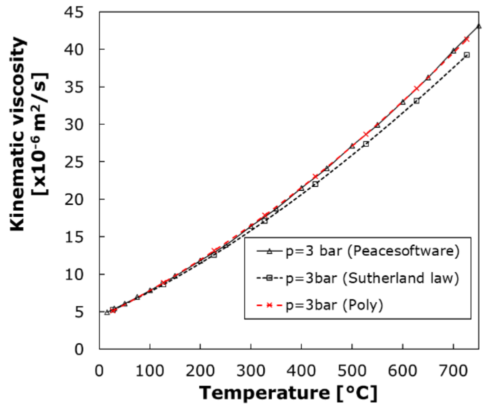
g) Density (p=3bar)



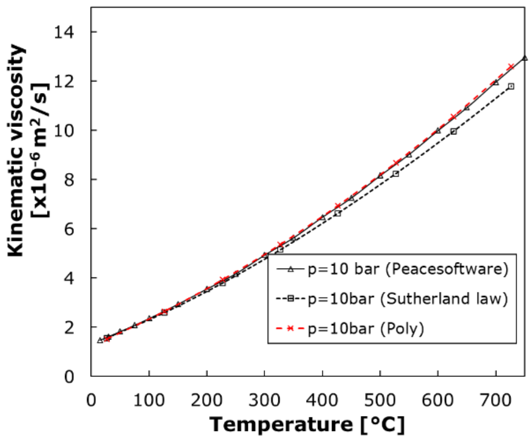
h) Density (p=10bar)



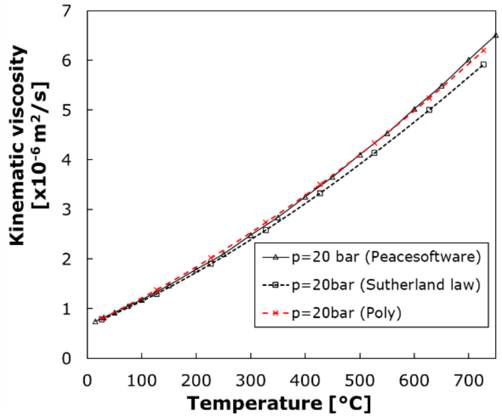
i) Density (p=20bar)



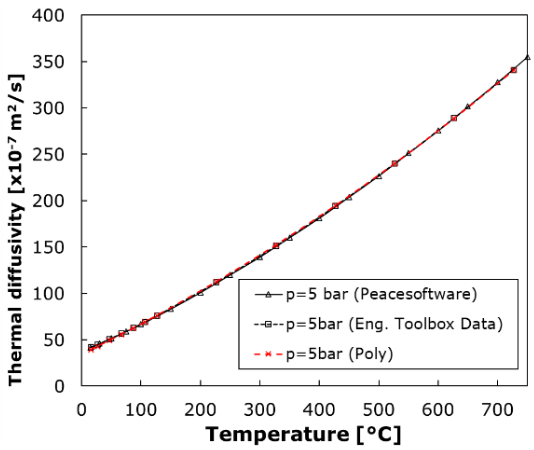
j) Kinematic viscosity (p=3bar)



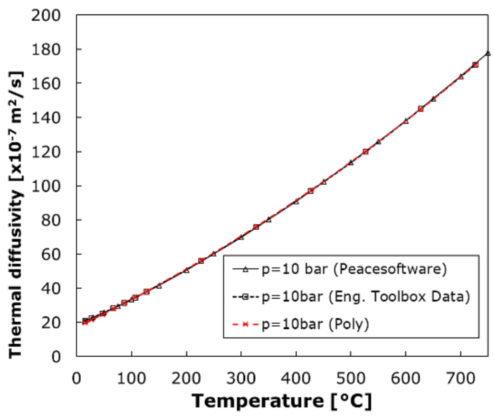
k) Kinematic viscosity (p=10bar)



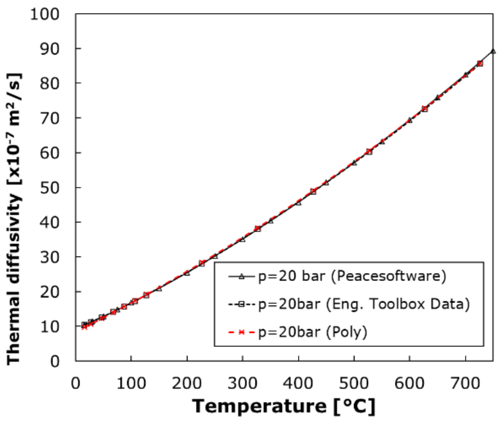
l) Kinematic viscosity (p=20bar)



m) Thermal diffusivity (p=3bar)



n) Thermal diffusivity (p=10bar)



o) Thermal diffusivity (p=20bar)

Fig. 14 Variation of the main parameters (original data vs poly fit data vs external source)

5.Conclusions

The requirements for environmentally friendly engines with lower emissions and improved specific consumption can be met by incorporating heat exchangers into gas turbines, which leads to an increased gas-turbine cycle efficiency by transferring the heat from the hot burnt gases to compressed air before entering the combustion chamber.

The heat exchanger design is an iterative complex process and involves a series of major considerations regarding thermal, hydraulic, and mechanical calculations, and other specific aspects.

Initial heat exchangers, that have been used in gas turbine systems, were essentially designed based on size limitation, reliability, and costs. They are usually of three types according to their heat transfer surface geometry, such as primary surface, plate-fin, and tubular recuperators.

To obtain a high-performance constructive solution for a plate-fin heat exchanger (in this case), with the desired performances imposed in the design theme, the influence of the geometric parameters and the main parameters that characterize the heat exchanger's performance must always be taken into consideration. The main geometric parameters which define the flow channels of a plate-fin heat exchanger are the distances Dpl1, Dpl2 between plates (fin hights) and the fin pitch p1,p2.

To choose the optimal geometric parameters, the variation of the heat exchanger's compactness comes in parallel with the variation of flow velocities through the channels. Thus, the working fluids, exhaust gas, and compressed air having different densities, it is necessary to differentiate the flow front surfaces so that the velocities of the two fluids have values as close as possible to the optimal flow through the heat exchangers, of 10÷30m /s.

The numerical method used proved to be sufficiently accurate so as to obtain relative errors of a maximum of 3%, obtaining values for the R^2 parameter of at least 99.74%. Maximum errors of 3% were recorded at extreme temperatures - minimum or maximum (for constant pressure), this being a limitation of the method for obtaining quadratic polynomials. It is observed from the average errors (obtained by averaging the absolute values of the errors) that the resulting polynomials deviate from the original solution by a maximum of ±1...2%. In general, the analyzed thermodynamic parameters do not appear in high-power terms involved in heat transfer formulas, so the errors introduced by polynomials do not amplify so much during the calculation process.

Future directions of research are to obtain even more general forms, perhaps of a higher order, which would better approximate the initial functions over a wider range of pressures and temperatures.

R E F E R E N C E S

[1*] J. Kurzke, I. Halliwell*, "Propulsion and Power", Springer International Publishing AG, ISBN 978-3-319-75977-7, https://doi.org/10.1007/978-3-319-75979-1

[2] GasTurb 13 Software, Design and Off-Design Performance of Gas Turbines Module, available at https://www.gasturb.de/Downloads/Manuals/GasTurb13.pdf

[3] *Thulukkanam, K.*, Heat Exchanger Design Handbook-Second Edition, CRC Press, 2013, ISBN 9781439842133

[4] *McDonald CF*. The increasing role of heat exchangers in gas turbine plants.

[5] *Chengyu Zhang, Volker Gummer*, High temperature heat exchangers for recuperated rotorcraft powerplants, Applied Thermal Engineering 154 (2019)

[6] *Lagerstrom G., Xie M*. High performance and cost effective recuperator for micro-gas turbine, 2002.

[7] *Shah RK*. Presented at Fifth international conference on enhanced, compact and ultra-compact heat exchangers: science, engineering and technology. Hoboken, NJ, USA, 2005.

[8] *Wiilson MA, Recknagle KP, Brooks K*. Design and development of a low-cost, high temperature silicon carbide microchannel recuperator. ASME Paper No. GT2005-69143; 2005.

[9] *Treece B, Vessa P, McKeirnan R*. Microturbine recuperator manufacturing and operating experience; 2002.

[10] *Jeong JH, Kim LS, Lee JK, Ha MY, Kim KS, Ahn YC*. Review of heat exchanger studies for high-efficiency gas turbines; 2007.

[11] *Tsai B, Wang YL*. A novel Swiss-Roll recuperator for the microturbine engine. Appl Therm Eng 2009;29:216–2.

[12*] Kesseli J, Wolf T, Nash J, Freedman S*. Micro, industrial, and advanced gas turbines employing recuperators; 2003.

[13] *McDonald CF*. Compact buffer zone plate-fin IHX—The key component for high-temperature nuclear process heat realization with advanced MHR. Appl Therm Eng 1996;16:3–32.

[14] *Abiko T, Tujii J, Eta T*. Plate fin type heat exchanger for high temperature. Google Patents; 2005.

[15] *Proeschel RA*. Proe 90TM recuperator for microturbine applications; 2002.

[16] *Shah, R. K.,* "Heat exchanger design methodology, in Heat Transfer Equipment Design" (R. K. Shah, E. C. Subbarao, and R. A. Mashelikar, eds.), Hemisphere, Washington, DC, 1988, pp. 17–22

[17*] Joel David Lindstrom*, “Design and evaluation of compact heat exchangers for hybrid fuel cell and gas turbine systems”, MONTANA STATE UNIVERSITY, April 2005
[18] *Kumari K, Yadav S*. “Linear regression analysis study.” J Pract Cardiovasc Sci 2018;4:33-6
[19] *Jennifer L. Kobrin, Sandip Sinharay, Shelby J. Haberman, and Michael Chajewski*, “An Investigation of the Fit of Linear Regression Models to Data from an SAT® Validity Study”, College Board Research Report 2011-3, ETS Research Report RR-11-19
[20] *Gibbs Y. Kanyongo, Janine Certo, Brown I. Launcelot*, “Using regression analysis to establish the relationship between home environment and reading achievement: A case of Zimbabwe”, International Education Journal, 2006, 7(5), 632-641. ISSN 1443, Shannon Research Press.
[21] *Nadler, Scott and Kros, John F.* (2007) "Forecasting with Excel: Suggestions for Managers," Spreadsheets in Education (eJSiE): Vol. 2: Iss. 2, Article 5. Available at: http://epublications.bond.edu.au/ejsie/vol2/iss2/5
[22] *G. Chen*, Polynomial Regression Models, Math Course 261A: “Regression Theory & Methods”, San José State University
[23] *Sunthornjittanon, Supichaya*, "Linear Regression Analysis on Net Income of an Agrochemical Company in Thailand" (2015). University Honors Theses. Paper 131. https://doi.org/10.15760/honors.137
[24] Peacesoftware, (2007). “Calculation of thermodynamic state variables of air.” [online] Available at: https://www.peacesoftware.de/einigewerte/luft_e.html
[25] S.*C.C. Bailey et al.,* Obtaining accurate mean velocity measurements in high Reynolds number turbulent boundary layers using Pitot tubes, J. Fluid Mech. (2013), vol. 715, pp. 642–670. c© Cambridge University Press 2013, doi:10.1017/jfm.2012.538
[26] *Mehmet Korkmaz,* "A study over the Formulation of the Parameters 5 or Less Independent Variables of Multiple Linear Regression", *Journal of Function Spaces*, vol. 2019, Article ID 1526920, 14 pages, 2019. https://doi.org/10.1155/2019/1526920
[27] *Ira Sharma and Sampurna Kakchapati,* Linear Regression Model to Identify the Factors Associated with Carbon Stock in Chure Forest of Nepal, Scientifica,Volume 2018, Article ID 1383482, 8 pages, https://doi.org/10.1155/2018/1383482
[28] *David J. Poferl, Roger A. Svehla, and Kenneth Lewandowski*, “Thermodynamic and transport properties of air and the combustion products of natural gas and of ASTM-A-1 fuel with air”, 1969, NASA TN D-5252
[29] *David J. Poferl and Roger A. Svehla*, “thermodynamic and transport properties of air and its products of combustion with ASTM-A-1 fuel and natural gas at 20, 30, AND 40 atmospheres”, 1973, NASA TN D-7488
[30] *R. L. Humphrey, C. A. Neel*, “tables of thermodynamic properties of air from 90 TO 15000 K”, 1961, AEDC-TN-61-103
[31] *Shpilrain*, E.E., AIR (properties of), DOI: 10.1615/AtoZ.a.air_properties_of, [online] Available at: https://www.thermopedia.com/content/553/
[32] Engineering ToolBox, (2018). Air - Thermal Diffusivity. [online] Available at: https://www.engineeringtoolbox.com/air-thermal-diffusivity-d_2011.html