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APPLYING ANALYTICAL HIERARCHY PROCESS TO SELECT THE PROPER MATERIAL USED IN CONSTRUCTION OF PLATE HEAT EXCHANGER WITH GASKETS

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Abstract: *The materials used in production of heat exchanger's plate plays an important function in the operation of this device, depending on the application area. Selecting the wrong plate material can lead to weight gain, that affects the costs of manufacturing, or worse, when using a material that is not compatible with the working agent circulated through the device, the effect is the damage of the product. Due to the wide range of materials with different properties, the material process of selecting is complex and time consuming. While choosing the right material for a specific application, manufacturers often require a systematic methodology to address this problem with several alternatives choices and conflicting objectives. The principles and techniques of Analytical Hierarchy Process were used to prioritize and select the proper material used in construction of plate heat exchanger with gasket. Sensitivity analysis was performed to increase the confidence in the choice of the proper material.*

Key words: *Material selection; Analytical Hierarchy Process; Plate heat exchanger with gaskets..*

1. INTRODUCTION

Heat exchangers are devices whose purpose is to transfer heat from one fluid to another, in processes of heating, cooling, heat recovery condensation, evaporation or other thermal processes where there are two or more fluids with different temperatures.

Plate heat exchangers are classified into three categories, depending on how they are built: the plate heat exchanger with gaskets, brazed and welded plate heat exchangers. The working agents that can be used are: liquid-liquid, liquid-gas or gas-gas.

The plate heat exchanger with gaskets (SCP-G), presented in figure 1, are composed from a set of individual plates mounted in a metal frame sealed tight with screws, glued or welded. Each pair of adjacent plates forms a flow channel, so that between two adjacent channels the flow direction of the two fluids is always counter. The plates (figure 2) are made of thin metal sheets, stainless steel, and are provided with undulations made by pressing, in order to increase stiffness and to improve heat transfer by increasing fluid turbulence.

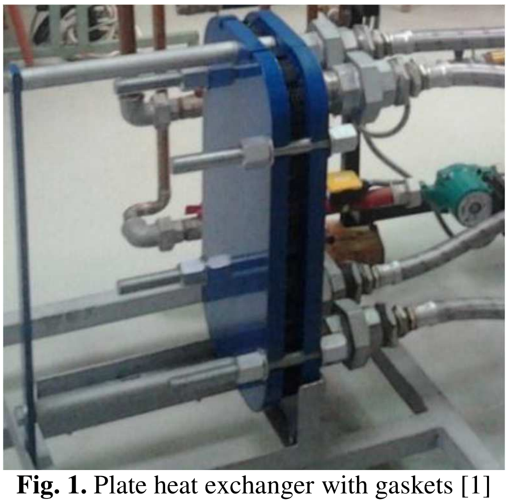


Fig. 1. Plate heat exchanger with gaskets [1]

Fig. 2. Plate model [1]

Plate sealing prevents interference between the thermal agents and also the drains. For this reason, it is extremely important, that the plate material to resist at these demands.

SCP-Gs have an important role in the operation in various branches of industry, as follow:

- food and drinks industry - cooling and pasteurization of milk and dairy products, fruit and vegetable juices, soft drinks, beer, cider and wine in the manufacture of ice cream, soups and baby food process industries,
- chemical and pharmaceutical industries - where high working pressures is required and it is necessary to take in account the protection of the environment, due to extremely corrosive and harmful substances. In this area, the plate heat exchangers are used in cooling and evaporation of water, acids, aqueous solutions which require thermal processing, heat recovery, condensation of steam and solvent vapors to protect the environment through the use of thermal processes in closed circuit.
- in heating and conditioning systems - heat exchangers are used for individual heating, industrial or urban, for domestic hot water, heat recovery systems, heat pumps, geothermal heat recovery systems and air conditioning plants.
- in the shipping industry - plate exchangers are used for cooling water and lubricants used in naval engines for heat recovery. These types of devices are preferred in this area due to compact design, high efficiency and low structure gauge.
- in industrial installations and processing - plate heat exchangers are used to heat or cool special thermal agents such as oils, salt solutions or caustic, as well are used for industrial chillers for welding machines, hydraulic presses, compressors, nuclear power plants, aeronautics, heat recovery in installations by dyeing, wastewater evaporation, liquid separation systems.
- in refrigerating applications - plate heat exchangers are used with the role of evaporator, condenser, super heater, sub cooler, intermediate cooler, heat recovery, oil coolers. In this area these devices are preferred because it can be used as working agent's organic solvents, water, various brine solutions (mixtures of glycol, calcium chloride, alcohols, etc.), viscous solutions (oil) and refrigerants [2].

The many areas in which these devices are used, is mainly due to the wide range of sizes and features associated with plate's material that allow their use in almost all thermal processes [3]. Obviously they have disadvantages like the pressure losses that occur due to gasket leakage, which increases pumping costs, limiting the pressure and temperature field required by the material of the gaskets [2]. Its inevitable need has necessitated work on efficient and reliable designs, have the best material for the plate leading towards optimum share in the overall system performance [4,5].

Material selection has great importance in the design and development of products, and it is also critical for the success and competitiveness of the producers [6,7]. Improper selection of materials may result in damage or failure of an assembly and significantly decreases the performance of products [8], thus negatively affecting productivity, profitability and reputation of an organization [9]. Each material has its own unique properties, which determines the quality and performance of the product. Therefore, it is crucial to select the appropriate materials for a particular design [10].

The selection of an optimal material for an engineering design from among two or more alternative materials on the basis of two or more attributes is a multiple attribute decision making problem. The selection decisions are complex, as material selection is more challenging today. There is a need for simple, systematic, and logical methods or mathematical tools to guide decision makers in considering a number of selection attributes and their interrelations.

The objective of any material selection procedure is to identify appropriate selection attributes, and obtain the most appropriate combination of attributes in conjunction with the real requirement. Thus, efforts need to be extended to identify those attributes that influence material selection for a given engineering design to eliminate unsuitable alternatives, and to select the most appropriate alternative using simple and logical methods [11].

Researchers and producers of the SCP-G area rely only on their experience when choosing the material of plate and gaskets for heat exchangers.

Until now we could not identify any studies that are based on objective criteria in the material selection for SCP-Gs. In specialized literature we identified a significant number of researches using AHP method to ranking different types of material in various fields, such as: material for solar flat plate collectors, material for polymeric composite automotive bumper, buildings materials, natural fiber reinforced polymer composites, material for an electroplating process, material handling equipment's, material for hacksaw blade, material selection of thermoplastic matrix for hybrid natural fiber / glass fiber polymer composites and so on. However, it should be noted, that no research refers to materials used in construction of SCP-Gs, therefore the novelty of this study.

The aim of this study was to solve the materials selection problem, i.e. identify the best material that can be used in construction of SCP-Gs, using the Analytical Hierarchy Process (AHP) methodology.

2. GASKETS MATERIALS AND THE OPERATING RANGE OF HEAT EXCHANGERS

Gaskets are elements that limit the pressure and temperature of plate heat exchangers. Some rubber-based composition allow operation at a pressure of 25 bar and a temperature of 150°C, and compositions based on special materials, allowing operation to 170°C (EPDM) ÷ 200°C (VITON). In table 1 are presented the materials for gaskets, corresponding with the operating range of heat exchangers.

In this study were compared seven materials used in the construction of plate's heat exchangers with gaskets that meet the above mentioned domains of utilization.

The properties of materials understudy are presented in Table 2. These are the main properties need for the selection of material because:

- thermal conductivity is the physical quantity which characterizes the ability of a material to transmit heat (through heat conduction) when is subjected to temperature differences. For this criterion higher values are preferred.
- specific heat represents thermal energy required for a quantity of the substance unit to increase its temperature by one degree without the process to produce a change of phase or state of aggregation. For this criterion higher values are preferred.
- the density, or more precisely, the volumetric mass density, of a substance is its mass per unit volume. In order to obtain a heat exchanger with low weight, density value has to be as low as possible. For this criterion smaller values are preferred.

Table 1

Gaskets materials and the operating range of heat exchangers [12]

Material	**Maximum temperature [°C]**				**Maximum pressure [bar]**			
G_1	110				10			
G_2	135				10			
G_3	130				15			
G_4	150				15			
G_5	150-170				25			
G_6	160-200				25			
G_7	260				20			
G_8	150-185				8			
Domain								
	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8
Water	x		x					
Food	x		x					x
Fat material		x		x				
Aldehydes				x				x
Cretonne				x				
Esters				x				x
Chemical products					x			x
Fuels						x		x
Mineral, vegetal and animals oils						x		x
Organic solvents							x	x

G_1 - Nitrile, G_5 - Fluorocarbon (Viton) TM,
G_2 - Acrylonitrile, G_6 - Pressed asbestos fiber,
G_3 - Butyl resin, G_7 - FKMT - Teflon gaskets

G_4 - Ethylene – propylene (EPDM),

Table 2

The properties of plate's materials.

Material /Property	M_1	M_2	M_3
Thermal conductivity [W/mK]	26	239.2	14.72
Specific heat [J/kgK]	445	936	494.3
Density [kg/m^3]	8800	2688	8210
References	[13,	[15]	[15, 16]

Material /Property	M_4	M_5	M_6	M_7
Thermal conductivity [W/mK]	16.14	20.8	60.1	27.2
Specific heat [J/kgK]	504.8	543.2	466.2	699
Density [kg/m^3]	7873	4491	7812	8220
References	[15,16]	[15,	[16]	[17]

M_1 – Monel - 67 Ni - 30 Cu - 1.4 Fe;
M_2 – Aluminum;
M_3 - Stainless Steel, type 316 - 17 Cr - 12 Ni - 2 Mo;
M_4 - Stainless Steel, type 304 - 18 Cr - 8 Ni;
M_5 – Titanium;
M_6 - Carbon Steel AISI1010;
M_7 – Hastelloy.

3. THE ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP), introduced by Thomas Saaty in 1980, is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision [18].

The AHP is a theory of measurement through pair wise comparisons and relies on the judgments of experts to derive priority scales. The comparisons are made using a scale of absolute judgments that represents how much more; one element dominates another with respect to a given attribute [19].

The methodology of the AHP can be implemented using the following steps:

Step 1: Decompose the problem into a hierarchy of goal, criteria and alternatives.

This is the most creative and important part of decision-making. Structuring the decision problem as a hierarchy is fundamental to the process of the AHP. Hierarchy indicates a relationship between elements of one level with those of the level immediately below. This relationship percolates down to the lowest levels of the hierarchy and in this manner every element is connected to every other one, at least in an indirect manner [20].

Figure 3 illustrates the hierarchical structure of the AHP method use to select the proper material for SCP-Gs.

Step 2: Establish the relative importance between two criteria.

The elements of each level are compared pair wise with respect to a specific element in the immediate upper level. Table 3 report the pair wise comparison scale used in the AHP developed by Saaty [21]. It allows converting the qualitative judgments into numerical values, also with intangible attributes.

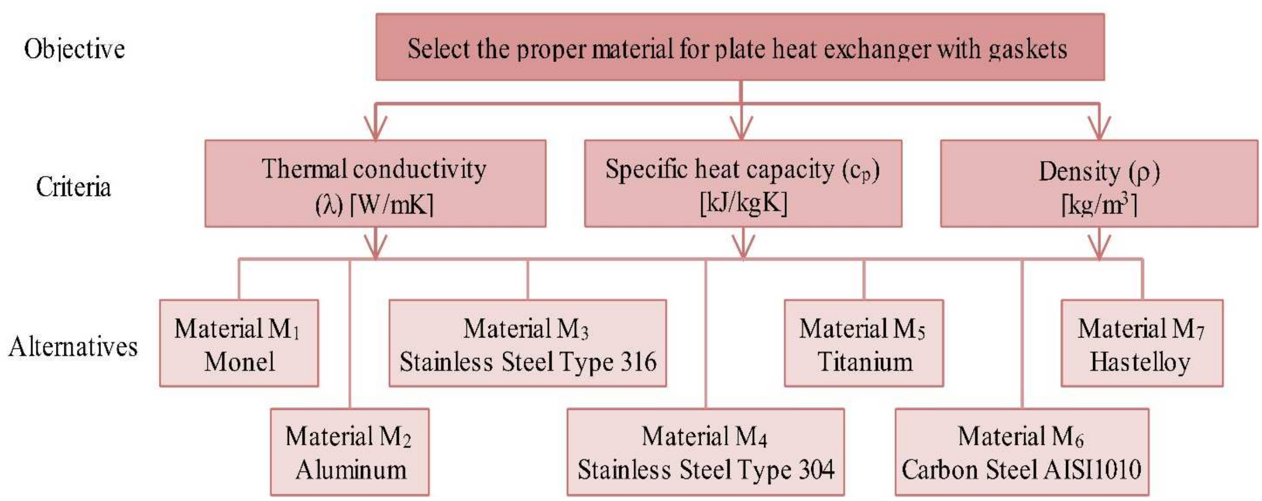


Fig. 3. The hierarchical structure of the AHP use to select the proper material for SCP-Gs

Table 3

The AHP pair wise comparison scale [21]

Nume-rical values	**Verbal scale**	**Explanation**
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgment favor one element over another
5	Strong importance of one element over another	An element is strongly favored
7	Very strong importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over another	An element is favored by at least an order of magnitude
2,4,6,8	Intermediate values	Used to compromise between two judgments

Step 3: Construct the judgments matrix as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & a_{ij} & \dots \\ a_{n1} & a_{n2} & \dots & a_{mn} \end{bmatrix} \quad (1)$$

where: A - the judgments matrix, a_{ij} – the pair wise comparison rating between the element i and the element j of a level with respect to upper level. The entries a_{ij} are governed by the following rules [21]:

$$a_{ij} \neq 0, \quad a_{ji} = \frac{1}{a_{ij}}, \quad a_{ii} = 1 \quad (2)$$

If a criterion is compared with it-self, then it is assigned to the value 1.

The judgment matrix is presented in table 4 for the goal of this case study, which was to select the proper material for plate heat exchanger. Tables 5-7 contain the judgment matrix for the criterion considered: thermal conductivity (λ), specific heat (cp) and the density (ρ).

Step 5: Find the relative normalized weight of each criterion by calculating the geometric mean of i-th row and normalizing the geometric means of row in the comparison matrix [22]:

$$GM_i = \left(a_{i1} \times a_{i2} \times \dots \times a_{ij}\right)^{\frac{1}{n}} \quad (3)$$

$$W_i = GM_i \Big/ \sum_{i=1}^{i=n} GM_i \quad (4)$$

where: W_i - the relative normalized weight of each criterion, GM_i - geometric means of i^{th} row.

Table 4

The judgment matrix for the goal of the case study

A	**λ**	**c_p**	**ρ**
λ	1	7	7
c_p	0.14286	1	5
ρ	0.14286	0.2	1

Table 5

The judgment matrix for the criterion thermal conductivity (λ)

λ	**M_1**	**M_2**	**M_3**	**M_4**	**M_5**	**M_6**	**M_7**
M_1	1	0.111	5	5	5	0.143	0.166
M_2	9	1	9	9	9	9	9
M_3	0.2	0.111	1	0.333	0.25	0.143	0.166
M_4	0.2	0.111	3	1	0.25	0.143	0.166
M_5	0.2	0.111	4	4	1	0.143	0.166
M_6	7	0.111	7	7	7	1	7
M_7	6	0.111	6	6	6	0.143	1

Table 6

The judgment matrix for the criterion specific heat (cp)

c_p	**M_1**	**M_2**	**M_3**	**M_4**	**M_5**	**M_6**	**M_7**
M_1	1	0.111	0.25	0.2	0.166	3	0.143
M_2	9	1	9	9	9	9	9
M_3	4	0.111	1	0.2	0.166	4	0.143
M_4	5	0.111	5	1	0.166	5	0.143
M_5	6	0.111	6	6	1	6	0.143
M_6	0.3	0.111	0.25	0.2	0.166	1	0.143
M_7	7	0.111	7	7	7	7	1

Table 7

The judgment matrix for the criterion the density (ρ)

ρ	M_1	M_2	M_3	M_4	M_5	M_6	M_7
M_1	1	0.111	0.25	0.2	0.166	3	0.143
M_2	9	1	9	9	9	9	9
M_3	4	0.111	1	0.2	0.166	4	0.143
M_4	5	0.111	5	1	0.166	5	0.143
M_5	6	0.111	6	6	1	6	0.143
M_6	0.3	0.111	0.25	0.2	0.166	1	0.143
M_7	7	0.111	7	7	7	7	1

Step 6: Obtain the matrix C which denote an n-dimensional column vector describing the sum of the weighted values for the importance degrees of alternatives, then [22]:

$$W = [W_1, W_2, ..., W_n] \quad (5)$$

$$C = A * W \quad (6)$$

$$C = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & a_{ij} & \dots \\ a_{n1} & a_{n2} & \dots & a_{mn} \end{bmatrix} * \begin{bmatrix} W_1 \\ W_2 \\ \dots \\ W_n \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \dots \\ c_n \end{bmatrix} \quad (7)$$

Step 7: Calculate the consistency values (CV) for the cluster of alternatives represented by the vector [23]:

$$CV_i = \frac{w_i}{c_i} \quad (8)$$

Step 8: Find out the maximum eigenvalue λ_{max} that is the average of the consistency values:

$$\lambda_{max} = \frac{\sum_{i=1}^{i=n} CV_i}{n} \quad (9)$$

where: n – the number of evaluated criteria [24].

Step 9: Calculate the inconsistency index, which is based on maximum eigenvalue:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (10)$$

where: CI – the inconsistency index [25].

Step 10: Compute the consistency ratio [26]:

$$CR = \frac{CI}{RI} \quad (11)$$

where: RI – random inconsistency [26]:

$$RI = 1{,}987 \cdot \frac{n - 2}{n} \quad (12)$$

Step 11: Verify the consistency of the matrix.

The measurement of consistency reflects whether the decision maker understands and captures the interactions among different factors of the problem or his decision is a matter of random hitting the target. However, perfect consistency is hard to achieve in real life problem solving [27]. If CR is less than 10%, then the matrix can be considered as having an acceptable consistency [28]. If CR<0.1, then the relative normalized weight of each criterion (Wi) will be considered as local weight of elements [24].

Step 12: Calculate the global weight of alternatives:

$$v(a_i) = \sum_k w_k \cdot S_k(a_i) \quad (13)$$

where: w_k – the local priority of the element k, $S_k(a_i)$ – the priority of alternative a_i with respect to element k of the upper level [21].

4. RESULTS AND DISCUSSION

Table 8 presents the results obtained from pair wise comparison matrix for the goal of the case study.

Table 8

Results obtained from pair wise comparison matrix for the goal of the case study

A	GM	Σ GMI	W	c	CV
λ	3.6593	4.85892	0.7531	2.4813	0.3035
cp	0.8939		0.1839	0.6061	0.3035
ρ	0.3057		0.0629	0.2073	0.3035
	Σ CV	λ_{max}	CI	RI	CR
A	0.9105	0.3035	-1.348	0.6623	-2.0356

Table 9-11 presents the results obtained from pair wise comparison matrix of alternatives respecting each criterion.

Table 9

Results obtained from pair wise comparison matrix of alternatives respecting thermal conductivity criterion

λ	GM	Σ GMI	W	c	CV
M 1	0.85378	12.9736	0.06581	0.58700	0.11211
M 2	6.57540		0.50683	4.94537	0.10249
M 3	0.23865		0.01840	0.15809	0.11636
M 4	0.32665		0.02518	0.21167	0.11895

M_5	0.50577		0.03898	0.33484	0.11643
M_6	2.93306		0.22608	2.15204	0.10505
M_7	1.54031		0.11873	1.09754	0.10818
	Σ CV	λ_{max}	CI	RI	CR
λ	0.77956	0.11137	-1.1481	1.41929	-0.8089

Table 10

Results obtained from pair wise comparison matrix of alternatives respecting specific heat criterion

c_p	GM	Σ GMI	W	c	CV
M_1	0.32665	12.9736	0.02518	0.21167	0.11895
M_2	6.57540		0.50683	4.94537	0.10249
M_3	0.50577		0.03898	0.33484	0.11643
M_4	0.85378		0.06581	0.58700	0.11211
M_5	1.54031		0.11873	1.09754	0.10818
M_6	0.23865		0.01840	0.15809	0.11636
M_7	2.93306		0.22608	2.15204	0.10505
	Σ CV	λ_{max}	CI	RI	CR
c_p	0.77956	0.11137	-1.1481	1.41929	-0.8089

Table 11

Results obtained from pair wise comparison matrix of alternatives respecting the density criterion

ρ	GM	Σ GMI	W	c	CV
M_1	0.23865	12.9736	0.01840	0.15809	0.11636
M_2	6.57540		0.50683	4.94537	0.10249
M_3	0.50577		0.03898	0.33484	0.11643
M_4	0.85378		0.06581	0.58700	0.11211
M_5	2.93306		0.22608	2.15204	0.10505
M_6	1.54031		0.11873	1.09754	0.10818
M_7	0.32665		0.02518	0.21167	0.11895
	Σ CV	λ_{max}	CI	RI	CR
ρ	0.77956	0.11137	-1.1481	1.41929	-0.8089

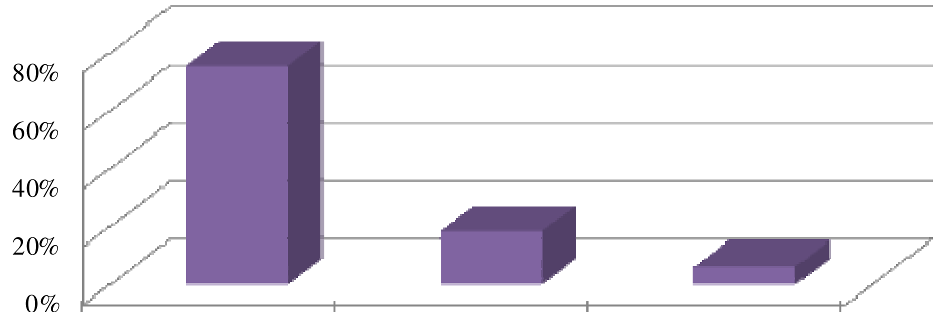
In figure 4 are illustrated the partial weights for the criterion considered in this case study. Figure 5 represents the partial weights for the alternatives studied respecting each criterion considered. The global weights of the alternatives studied are presented in figure 6.

This study was performed in order to determine the best material for the plates that are used in the construction of these heat exchangers – devices, using AHP method. Considering the multitude of materials existing on the market, with different thermo-physical properties, this research focused on those that closely match with the fields of application presented above. SCP-Gs can be assembled in any combination of materials for plates and gaskets taking into account the operating range, the maximum temperature and pressure required by the systems.

From result obtained we observe that the consistency ratio (CR) is less than 0.1 (10%), that mean the matrix can be considered as having an acceptable consistency and the relative normalized weight of each criterion (W_i) will be considered as local weight of elements.

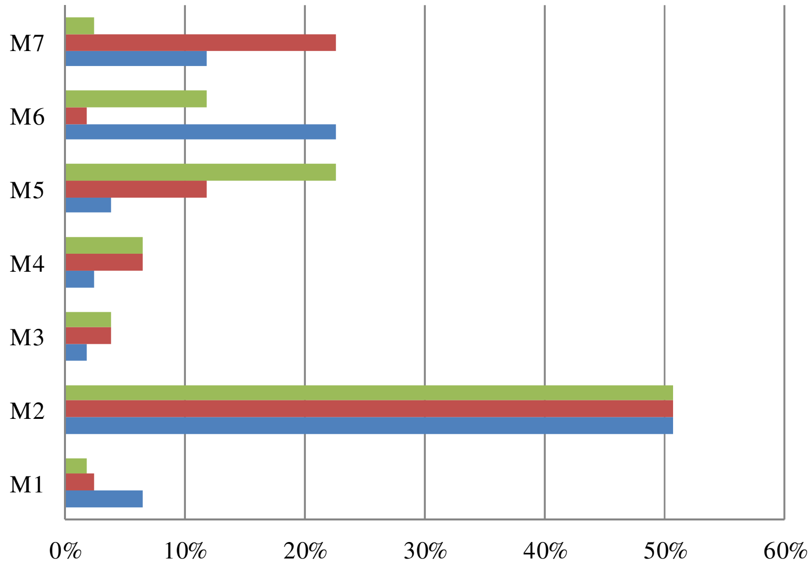
From Figure 4 results that the main criteria according to which plate material selection should be realized should be: thermal conductivity criterion (which obtained the local weight of 75.31109%). The second criterion, with a percentage of 18.39717% that must be considered is the specific heat of material. Weight of density criterion is 6.29174%, which means that the weight of the exchanger SCPG is not very important.

Figure 5 shows that all seven materials who have been subjected to study obtained different weights for the three criteria considered. The material M_2 (Aluminum) is the only one who got the same weight (50.683%) for all three studied criteria, which means it is the best choice in the construction of plate heat exchangers.



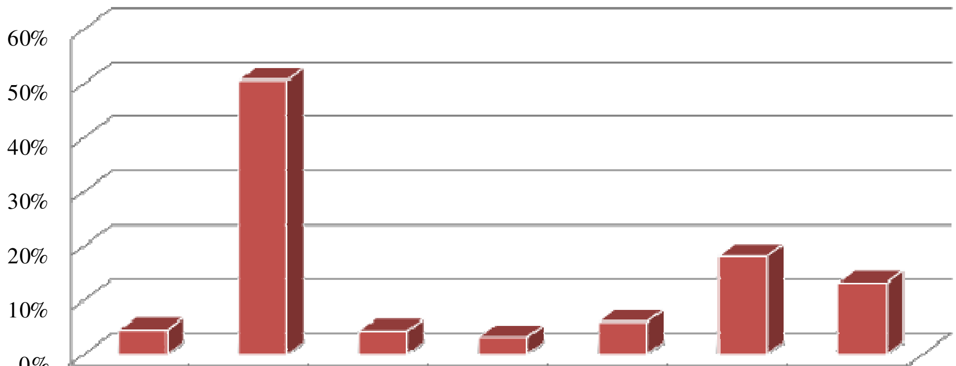
	For criterion λ	For criterion cp	For criterion ρ
w	75.31109%	18.39717%	6.29174%

Fig. 4. Partial weights for the criterion considered



	M1	M2	M3	M4	M5	M6	M7
Taking into account the judment matrix ρ	1.840%	50.683%	3.898%	6.581%	22.608%	11.873%	2.518%
Taking into account the judment matrix cp	2.518%	50.683%	3.898%	6.581%	11.873%	1.840%	22.608%
Taking into account the judment matrix λ	6.581%	50.683%	1.840%	2.518%	3.898%	22.608%	11.873%

Fig. 5. Partial weights for the alternatives considered



	M1	M2	M3	M4	M5	M6	M7
v	4.53%	50.68%	4.29%	3.12%	6.04%	18.11%	13.23%

Fig. 6. Global weights of the alternatives

With a local weight of 22,608%, the second option is:

- The material M_5 (Titanium) from the point of view of density criterion;
- The material M_6 (Carbon Steel AISI1010) if we take into account only the thermal conductivity criterion;
- The material M_7 (Hastelloy) if we consider only the specific heat criterion.

From figure 6 we can observe that ranking of the materials studied using global weights obtained using AHP method is: M_2 (Aluminum), M_6 (Carbon Steel AISI1010) and respectively M_7 (Hastelloy).

5. CONCLUSIONS

Most of researchers and the manufacturers use in construction of the SCP-Gs that materials with are familiar. Selection of materials is based only on their experience. To improve the quality of decision and reduce the risk of a poor selection of the material used in construction of the SCP-Gs is needed a systematic evaluation, which can be obtained using the AHP method. With additional criteria the AHP method can be reiterated for future research.

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Aplicarea procesului de analiza ierarhică pentru selectarea materialului potrivit utilizat în construcția schimbătoarelor de căldură cu plăci și garnituri

Rezumat: Materialele utilizate în producția schimbătoarelor de căldură cu plăci și garnituri joacă un rol important în funcționarea acestor dispozitive, în funcție de domeniul de aplicare. Selectarea greșită a materialului pentru placă poate duce la creșterea gabaritului, care afectează costurile de producție, sau mai rău, atunci când se utilizează un material care nu este compatibil cu agentul de lucru circulat prin dispozitiv, efectul duce la deteriorarea produsului. Datorită gamei largi de materiale cu proprietăți diferite, procesul de selecție a materialului este complex și consumator de timp. Identificarea materialului potrivit pentru o aplicație specifică necesită o metodologie sistematică. Principiile și tehnicile procesului de analiză ierarhică au fost folosite pentru a prioritiza și selecta materialul adecvat utilizat în construcția plăcilor schimbătoarelor de căldură. Analiza senzitivității a fost realizată pentru a crește gradul de încredere în alegerea materialului adecvat.

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