

Multi-criteria decision making analysis in refrigerant selection for residential heat pump systems

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Abstract

The concern on global warming has resulted in a global decision to reduce use of refrigerants with high global warming potential (GWP). This implies that a number of refrigeration and heat pump systems need to adopt new refrigerants that have low GWP and satisfy a number of important criteria as for instance good thermophysical and transport properties, safety, stability and etc. As none of the known refrigerants is superior to the others in respect to all the selection criteria, choosing refrigerant is always a complex decision-making process that is based on a number of important criteria. In this paper we investigate the applicability of an analytical hierarchy process method for multi-criteria decision making of selecting a refrigerant for a heat pump system. Potential low GWP refrigerants are studied and important refrigerant selection criteria are considered. The criteria are weighted for each of the alternative refrigerant in order to rank different refrigerant alternatives. The method is applied from perspective of a number of stakeholders. The results suggest that it is possible to identify the refrigerant alternative that is optimal for a given application, using the process presented in the paper. Thus, the results of this paper show the applicability of utilizing the multi-criteria decision making analysis in unbiased refrigerant selection for residential heat pump systems.

Keywords: decision-making; low GWP; refrigerant selection; analytical hierarchy process; AHP

1. Introduction

The global climate observations show continuous increase of the Earth's global mean temperature [1] and its current recordings show that the year 2016 was the warmest year since modern recordkeeping began in 1880 [2]. In response to the threat of climate change many countries have agreed to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature

Nomenclature

AHP	analytic hierarchy process
C.I.	consistency index
C.R.	consistency ratio
CR	criterion
F-gases	fluorinated gases
HFC	hydrofluorocarbons
HP	heat pump

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λ_{\max}	principal eigenvalue
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increase to 1.5 °C above pre-industrial levels [3]. Strong and decisive action promoting energy efficiency and the deployment of renewable energy sources is needed in order to limit the increase of average global temperature to 2 °C. Heat pumps are seen as a component in the efficient solutions to meet such climate targets [4].

Conventional heat pump technology relies on utilization of the vapor compression refrigeration cycle that uses refrigerant to transfer energy from a heat source to a heat sink. Heat pumps traditionally use hydrofluorocarbons (HFCs) as refrigerants [4]. HFC refrigerants are strong greenhouse gases and therefore their use should be reduced to mitigate the global warming. Such reduction is now scheduled globally within the mechanisms of the Montreal Protocol [5]. In the European Union the HFC phase down schedule is regulated by the European Regulation 517/2014 on fluorinated gases (F-gases), that requires a gradual reduction of F-gases to the 21 % of the baseline level (2009-2012 average) [6]. Moreover, a major reduction to the 63 % of baseline should happen by 1 January 2018.

Given the above discussed trends, future heat pumps will have to rely on the use of alternative refrigerants with low global warming potential. While the list of potential single component environmentally friendly refrigerants is limited [7] the number of refrigerant mixtures is growing and now consists of a large number of potential refrigerants [8][9].

To prefer one refrigerant over another for a heat pump application one needs to trade-off between different options. Ideally, a refrigerant should satisfy a number of properties that, for instance, can include [10]:

- high latent heat of vaporization
- high suction gas density
- positive but not excessive pressures at evaporating and condensing conditions
- chemical stability, compatibility with construction materials, miscibility with lubricants
- non-corrosive, non-toxic and non-flammable
- high dielectric strength
- environmentally friendly
- low cost

Some of the above listed properties are compulsory, as for instance no (or extremely low) ozone depletion potential, material compatibility and etc. Many other properties, as for instance high latent heat of vaporization and low cost are preferable, and can be compromised in favor of other properties depending on stakeholder's preferences. The decision making process on preferring one refrigerant (with a specific set of properties) over another, is therefore a multi-criteria decision making process. While the selection of a refrigerant is a common process, it is prone to a biased decision based on the "rules of thumb" of a specific person that makes the decision. In this paper we approach the refrigerant selection process as a multi criteria decision making process and therefore apply relevant tools.

This paper is focused on the selection of new environmentally friendly refrigerants for heat pump (HP) unit using the analytical hierarchy decision making process.

2. Methodology

The analytic hierarchy process (AHP), as developed by Saaty [11], has been used in this study. The AHP is applied to the refrigerant selection decision making where decision is being made based on the alternatives' global priorities that are obtained following the steps in detail described in [12], namely:

- structuring of the problem as a hierarchy;
- elicitation of pairwise comparison judgments;
- establishing the composite (global) priorities of the alternatives.

The pairwise comparison between a set of refrigerant selecting criteria has been facilitated with the stakeholders' questionnaire results. The questionnaire answers have been obtained from eight different stakeholders relevant to heat pump development and therefore depict a representative set of opinions.

The pairwise comparisons of analyzed refrigerant alternatives are made based on the available knowledge and, where relevant, supported by the review of their thermodynamic properties.

3. Analytic hierarchy process of refrigerant selection

3.1 The structuring of the problem as a hierarchy

The first step of AHP is the structuring of the problem as a hierarchy. In the top level of the hierarchy, Figure 1, is our goal of selecting refrigerant for a HP application. At the second level there are eight criteria which are assessed to contribute to the goal. And the third level of the current hierarchy are the three alternative refrigerants which are evaluated in terms of the criteria in the second level.

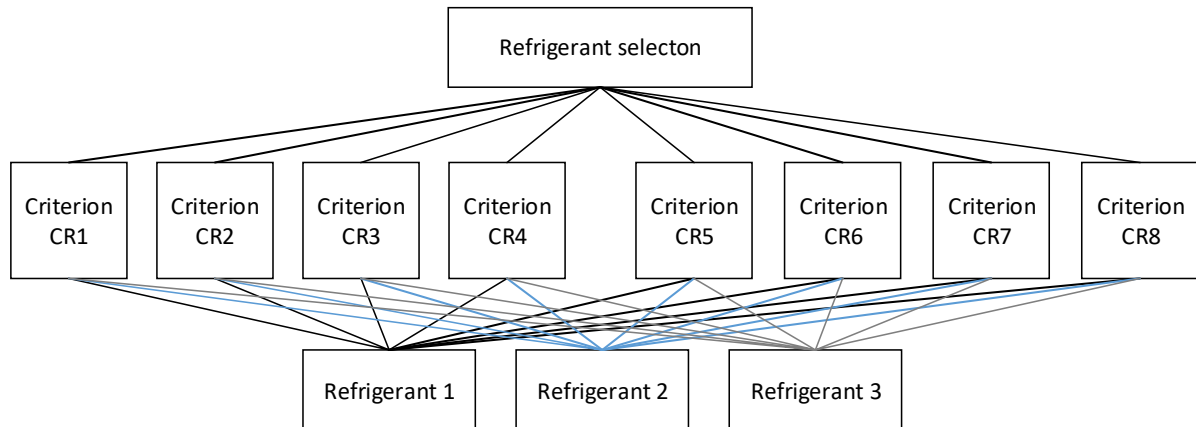


Figure 1. Decomposition of the refrigerant selection problem into a hierarchy

A number of the refrigerant selection criteria have been applied. These are:

- Low condensing pressure, CR1;

Keeping the condensing pressure low (e.g. lower than 25 bar) is essential to the heat exchanger design as can allow using aluminum in a brazed plate heat exchanger configuration. Lower pressures also allow using cheaper HP components consequently lowering the cost of the HP system. On the other hand, systems with high pressures (R410A refrigerant) are widely used on the market.

- High volumetric capacity, CR2;

Volumetric heating capacity is the product of the heating effect of the heat pump (enthalpy difference between condenser inlet and outlet) and refrigerant density at the compression inlet. The higher volumetric heating capacity, the smaller refrigerant volumetric flow is required to cover a specific heating load. It therefore allows using a smaller compressor, leads to smaller unit size, and consequently to lower unit cost.

- Low compressor discharge temperature, CR3;

Compressor discharge temperatures are advised to be below a certain temperature limit. If refrigerant thermodynamic properties suggest very high compressor discharge temperature, it can be reduced by using alternative techniques, as for instance the refrigerant vapor injection during the compression. This complicates the process and leads to an increased maintenance and unit cost.

- Low refrigerant cost, CR4;

Cost of refrigerant varies greatly, and currently some unsaturated HFCs tend to have the highest costs. Lower refrigerant cost is preferable.

- Low system cost, CR5;

Refrigerant choice influences the system design. For instance, the use of highly flammable refrigerants (e.g. hydrocarbons) in systems with high refrigerant charge will likely increase system cost to ensure safe design of the system. Likewise, the use of CO₂ requires components that are able to withstand high pressures and are generally more expensive than the components for HFC refrigerants. Lower system cost is preferable.

- Natural refrigerant, CR6;

Hydrocarbons are examples of, so called, “natural” refrigerants. The use of “natural” refrigerant is advisable as it can be seen as a long term solution due to their favorable environmental properties and well-studied drawbacks. Additionally, the use of HFCs is known to be reduced globally in the future.

- Low(no) flammability, CR7;

Nonflammable refrigerants are preferred from a safety stand point. As many new refrigerants are flammable, the use of a mildly flammable refrigerant can be preferred to a flammable or a highly flammable one.

Good environmental performance, CR8;

Refrigerants have an impact on environment at many levels. The use of a more environmentally friendly refrigerant is therefore preferred. However, the direct environmental impact of a refrigerant (expressed in its global warming potential) is often accompanied by its flammability.

3.2 The elicitation of pairwise comparison judgments

In order to facilitate ranking of the relative importance of the refrigerant selection criteria with respect to the overall goal of selecting the best refrigerant for a HP, a number of stakeholders were asked to rank the criteria in a range from 1 (not important at all) to 8 (extremely important), with the requirement to have each rank to be assigned only once. The compiled response summary is presented in Table 1.

Table 1. Stakeholders' rating of relative importance

Criterion	SH1	SH2	SH3	SH4	SH5	SH6	SH7	SH8	SH1..SH8 average	Standard deviation
Low condensing pressure, CR1	8	5	2	1	7	7	5	8	5.4	2.5
High volumetric capacity, CR2	7	6	6	7	4	8	6	7	6.4	1.1
Low compressor discharge temperature, CR3	3	3	3	6	5	6	7	3	4.5	1.6
Low refrigerant cost, CR4	1	4	4	2	2	1	1	1	2.0	1.2
Low system cost, CR5	6	7	8	4	3	2	3	6	4.9	2.0
Natural refrigerant, CR6	4	1	5	5	1	4	2	4	3.3	1.6
Low(no) flammability, CR7	5	2	1	3	8	3	4	5	3.9	2.0
Good environmental performance, CR8	2	8	7	8	6	5	8	2	5.8	2.4

The response results are then used in pairwise comparison of the criteria using the scale from 1 to 9, in according to the classification given in the Table 2. The numbers of this scale indicate how many times more important or dominant one alternative is over another alternative with respect to the criterion to which they are compared.

Table 2. The fundamental scale [11]

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	The activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

Based on the questionnaire results in Table 1 and applying the scale, as in Table 2, the pairwise comparisons a_{ij} between criteria are made, as listed in the Table 3. Here, pairwise comparisons are based on the average values obtained from the questionnaire. We realize, however, that the average values do not represent each of the

stakeholders that took part in the questionnaire. For instance, the importance of the criterion CR1 is ranging from 1 (not important at all) to 8 (extremely important). However, the current study is focused on application of the AHP method to the process of refrigerant selection. More advanced score aggregation technique and more detailed pairwise comparisons are advisable, but is not the focus of this study.

The maximum intensity of importance on an absolute scale of Table 1 has been assigned to the pairs where the average rating obtained from the stakeholders' response differs the most. For instance, high volumetric capacity CR2 has average rating 6.4, maximum of all the 8 criteria and the low refrigerant cost CR4 has average rating of 2.0, which is the minimum of all the assessed criteria. In pairwise comparison of CR2 with CR4, we define CR2 as extremely more important criterion in comparison to CR4 and assign intensity of importance value 9. The reciprocal value of pairwise comparison of CR4 to CR2 is therefore inverse of 9 – 1/9 (or 0.1). The lowest intensity of importance of one criterion over another is assigned to pairs where their average rank is similar. Thus, on average the Good environmental performance CR8 (5.8 average rank) can be considered to be slightly more important than low condensing pressure CR1 (5.4 average rank) and therefore we assign 1.7 intensity value to this pairwise comparison. The rest of the values follow similar considerations.

Further the scale of the priorities for the given criteria (also known as weights) is derived. The weights vector W_i can be generated for the matrix of judgments A in Table 3 by normalizing the vector in each column of the matrix by dividing each entry of the column by the column total (Equation 1), and averaging over the rows of the resulting matrix (Equation 2). The calculation results are presented in Table 4.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (1)$$

$$w_i = \frac{\sum_{j=1}^n b_{ij}}{n} \quad (2)$$

Table 3. Pairwise comparison matrix for level 1

Criterion	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8
Low condensing pressure, CR1	1	0.4	2.6	7.2	1.9	4.8	3.7	0.3
High volumetric capacity, CR2	2.8	1	4.5	9.0	3.7	6.6	5.5	2.1
Low compressor discharge temperature, CR3	0.4	0.2	1	5.5	0.3	3.2	2.1	0.3
Low refrigerant cost, CR4	0.1	0.1	0.2	1	0.2	0.3	0.2	0.1
Low system cost, CR5	0.1	0.3	1.7	6.3	1	3.9	2.8	0.4
Natural refrigerant, CR6	0.2	0.2	0.3	3.4	0.3	1	0.5	0.2
Low(no) flammability, CR7	0.3	0.2	0.5	4.5	0.4	2.1	1	0.2
Good environmental performance, CR8	1.7	0.5	3.4	7.9	2.6	5.5	4.5	1

Table 4. Priority vector computation

Criterion	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	Priority vector w
Low condensing pressure, CR1	0.152	0.138	0.183	0.161	0.183	0.175	0.182	0.065	15.5%
High volumetric capacity, CR2	0.424	0.345	0.317	0.201	0.356	0.241	0.271	0.457	32.6%
Low compressor discharge temperature, CR3	0.061	0.069	0.070	0.123	0.029	0.117	0.103	0.065	8.0%
Low refrigerant cost, CR4	0.015	0.034	0.014	0.022	0.019	0.011	0.010	0.022	1.8%
Low system cost, CR5	0.015	0.103	0.120	0.141	0.096	0.142	0.138	0.087	10.5%
Natural refrigerant, CR6	0.030	0.069	0.021	0.076	0.029	0.036	0.025	0.043	4.1%
Low(no) flammability, CR7	0.045	0.069	0.035	0.100	0.038	0.077	0.049	0.043	5.7%
Good environmental performance, CR8	0.258	0.172	0.239	0.176	0.250	0.201	0.222	0.217	21.7%

The resulting priority vector (vector of relative weights) is $w = (0.155, 0.326, 0.080, 0.018, 0.105, 0.041, 0.057, 0.217)$.

The consistency of the pairwise comparison matrix needs to be checked in order to ensure the consistency of the input values for the analysis. The consistency check process follows the AHP methodology in detail described in [11]. First, the principal eigenvalue λ_{\max} is obtained from the Equation 3.

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(\mathbf{Aw})_i}{w_i} \quad (3)$$

Solving Eq.1 we obtain $\lambda_{\max} = 8.23$. The consistency index C.I. is then calculated using the Equation 4.

$$C.I. = \frac{(\lambda_{\max} - n)}{n - 1} = 0.033 \quad (4)$$

Finally, the consistency ratio C.R. is calculated as a ratio of C.I. to the random consistency index R.I., which for the 8x8 matrix (n=8) is known to be 1.41 [11]. Thus, the resulting C.R. is 0.02. Since the C.R. value is below 0.1, the matrix is considered consistent and can be used for further analysis.

A similar process applies to the pairwise comparison of the alternative refrigerants in respect to each of the analyzed criteria. To facilitate the judgements, a brief analysis of the three refrigerant alternatives has been performed in respect to their use in a residential heat pump unit designed to operate at 5 °C evaporating temperature, 45 °C condensing temperature, 5 °C superheating and subcooling, 70 % compression isentropic efficiency. Main properties of the three alternative refrigerants are summarized in the Table 5.

Table 5. Main characteristics of refrigerants R1234ze(E), R152a and R290

Refrigerant	R1234ze(E)	R152a	R290
GWP [13], -	1	138	3*
ASHRAE safety classification	A2L	A2	A3
Critical temperature, °C	109.4	113.3	97.0
Critical pressure, bar	36.4	45.2	42.5
NBP, °C	-19.0	-24.0	-42.1
<i>Vapor compression cycle data:</i>			
Evaporating pressure @5°C, bar	2.59	3.148	5.51
Condensing pressure @45°C, bar	8.76	10.37	15.34
Heating effect, kJ kg ⁻¹	170.60	302.94	352.47
Density at compressor inlet, kg m ⁻³	13.60	9.65	11.65
Volumetric heating capacity, kJ m ⁻³	2319.80	2924.45	4107.58
COP heating	5.09	5.21	5.02
Compressor discharge temperature, °C	57.1	74.6	63.2

*indirect GWP as listed in [14]

Table 6 presents the results of pairwise comparison of the alternative refrigerants for criteria CR1 and CR2. In respect to criterion CR1 (low condensing pressure) all 3 refrigerants equally satisfy requirement of condensing pressure below 25 bar under various HP operation scenarios. As all the alternatives contribute equally to the objective we set intensity of importance 1 on the absolute scale given in Table 2. As for the criterion CR2 (high volumetric capacity), R290 clearly superior to R152a and R1234ze, whereas the volumetric capacity of R152a is slightly higher than that of R1234ze(E).

Table 6. Comparison matrices and local priorities for CR1 and CR2

CR1	R1234ze(E)	R152a	R290	Priority vector	CR2	R1234ze(E)	R152a	R290	Priority vector
R1234ze(E)	1	1	1	33.3%	R1234ze(E)	1	1/3	1/9	7.0%
R152a	1	1	1	33.3%	R152a	3	1	1/6	16.6%
R290	1	1	1	33.3%	R290	9	6	1	76.4%
$\lambda_{\max}=3.00$, CI=0.00, CR=0					$\lambda_{\max}=3.05$, CI=0.03, CR=0.05				

Table 7 presents the results of pairwise comparison of the alternative refrigerants for criteria CR3 and CR4. In respect to criterion CR3 (low compressor discharge temperature) all 3 refrigerants equally satisfy requirement of compressor discharge temperature being within limit that is considered safe for compressor operation in the typical for heat pump operating temperatures range. As all the alternatives contribute equally to the objective we set intensity of importance 1 on the absolute scale given in Table 2.

The cost of refrigerant varies over time (with growing scale of R1234ze(E) production we can expect lowering of its price; as demand for R152a is currently low, its price can be somewhat elevated), and territory (e.g. HFC taxation in several countries as Denmark and Norway). Thus, the pairwise comparisons between the refrigerants in regard to CR4 are based on the insufficient knowledge and only indicative for this study. For appropriate analysis it is necessary to call upon the advice of experts in order to obtain proper pairwise comparisons.

Table 7. Comparison matrices and local priorities for CR3 and CR4

CR3	R1234ze(E)	R152a	R290	Priority vector	CR4	R1234ze(E)	R152a	R290	Priority vector
R1234ze(E)	1	1	1	33.3%	R1234ze(E)	1	1/7	1/3	5.7%
R152a	1	1	1	33.3%	R152a	7	1	1/5	29.5%
R290	1	1	1	33.3%	R290	9	3	1	64.9%
$\lambda_{\max}=3.00$, CI=0.00, CR=0					$\lambda_{\max}=3.08$, CI=0.41, CR=0.07				

Table 8 presents the results of pairwise comparison of the alternative refrigerants for criteria CR5 and CR6. The pairwise comparisons of criterion CR6 (natural refrigerant) are self-explanatory, considering that only R290 is a natural refrigerant among the analysed alternatives. As for the system cost of the HP system, it can be mainly influenced by the difference in flammability characteristics between the refrigerants, different volumetric heating capacity values and refrigerant cost. It will be additionally influenced by such factors as component availability, pipe sizing and etc. The values presented for pairwise comparisons for CR5 are considered satisfactory for the purpose of this study, but should be re-evaluated for more comprehensive refrigerant selection analysis.

Table 8. Comparison matrices and local priorities CR5 and CR6

CR5	R1234ze(E)	R152a	R290	Priority vector	CR6	R1234ze(E)	R152a	R290	Priority vector
R1234ze(E)	1	2	3	52.5%	R1234ze(E)	1	1	1/9	9.1%
R152a	1/2	1	3	33.4%	R152a	1	1	1/9	9.1%
R290	1/2	1/3	1	14.2%	R290	9	9	1	81.8%
$\lambda_{\max}=3.05$, CI=0.03, CR=0.05					$\lambda_{\max}=3.00$, CI=0.0, CR=0.0				

Table 9 presents the results of pairwise comparison of the alternative refrigerants for criteria CR7 and CR8. While all 3 refrigerants in our comparison are flammable, their flammability varies with R290 being highly flammable refrigerant (A3 safety classification) and R152a being flammable (A2). In comparison, the flammability of R1234ze(E) is very low (A2L safety classification).

The overall environmental performance is taken into account to assess the pairwise comparisons of refrigerants in regard to the criterion CR8. Both R290 and R1234ze(E) have low GWP and comparable energy efficiency (at the modelled conditions shown in Table 5). R152a is the most energy efficient among the analysed refrigerants, but have higher GWP value. The difference can be noted in the decomposition products of R1234ze(E) and R152a in comparison to R290, where R290 can be considered more environmentally friendly. As reliable pairwise comparisons of the refrigerants in regard to the criterion CR8 require additional investigation, the values listed in the Table 8 are used for indicative purposes of current analysis and needs to be further refined for more detailed study.

Table 9. Comparison matrices and local priorities CR7 and CR8

CR7	R1234ze(E)	R152a	R290	Priority vector	CR8	R1234ze(E)	R152a	R290	Priority vector
R1234ze(E)	1	5	9	74.8%	R1234ze(E)	1	1	1/2	25.0%
R152a	1/5	1	3	18.0%	R152a	1	1	1/2	25.0%
R290	1/9	1/3	1	7.1%	R290	2	2	1	50.0%
$\lambda_{\max}=3.03$, CI=0.02, CR=0.03					$\lambda_{\max}=3.00$, CI=0.00; CR=0.00				

3.3 Establishing of the global priorities of the alternatives

The global priorities of the alternative refrigerant are calculated by summing up the products of the local priorities of the alternatives with the local priorities of the criteria, Table 10. The results indicate that the least desirable alternative is refrigerant R1234ze(E), closely followed by the R152a. The best refrigerant for our heat pump based on the average rank of the analyzed stakeholders' opinion is R290.

Table 10. Local and global priorities

	CR1 (0.155)	CR2 (0.326)	CR3 (0.080)	CR4 (0.018)	CR5 (0.105)	CR6 (0.041)	CR7 (0.057)	CR8 (0.217)	Global priority
R1234ze(E)	0.333	0.070	0.333	0.057	0.525	0.091	0.748	0.250	0.258
R152a	0.333	0.166	0.333	0.295	0.334	0.091	0.180	0.250	0.241
R290	0.333	0.764	0.333	0.649	0.142	0.818	0.071	0.250	0.501

It can be seen that the result is highly influenced by high volumetric heating capacity of R290 (local priority 0.764) coupled with high relative weight (0.326) given to this criterion by the stakeholders. R290 is also preferred to other alternatives as natural refrigerant (local priority 0.818), but due to the low relevance of this property to the stakeholders (relative weight 0.041) this criterion had low contribution to the global priority value. Similarly, R1234ze(E) is the least flammable refrigerant among selected, but since for the current case study this parameter has been identified to be of low importance (relative weight 0.057), it had slight contribution to R1234ze(E) global priority. In alternative case, where the stakeholders might identify flammability as a very important selection characteristic, this refrigerant can become more preferable.

4. Conclusion

The current work approaches the problem of refrigerant selection for a heat pump system. The problem can be introduced as a typical multi-criteria decision making problem with several criteria involved. Analytical hierarchy process decision making tool is utilized in this work in order to facilitate refrigerant selection for a heat pump system. This tool is known to be used for selection of one alternative from a given set of alternatives, usually where there are multiple decision criteria involved.

In order to utilize this multi criteria decision making tool the problem has been presented as a hierarchy that contains the assessed criteria and the considered refrigerant alternatives. The stakeholders' opinions were compiled and used to perform pairwise comparisons on the effect of each refrigerant selection criteria to the refrigerant selection goal.

Refrigerants R1234ze(E), R152a and R290 were mutually compared in regard to their suitability to fulfil goals within the scope of each of the criteria separately. The result of the AHP shows that R290 is the most preferred alternative for all the stakeholders that were involved in presented refrigerant selection, whereas R152a and R1234ze(E) are the least preferred alternatives.

The results of the analysis are highly dependent on the assigned ratings of pairwise comparisons. The ratings have been assigned to pairwise comparisons between a set of refrigerant selection criteria in regard to the goal of refrigerant selection, as well as the pairwise comparison of refrigerant alternatives in regard to each of the refrigerant selection criteria. While the reliable comparisons between refrigerants can be achieved by utilizing expert knowledge and available data, the pairwise comparisons of relative importance of different criteria is dependent on the stakeholder's personal knowledge, view and opinion. The results of the analysis are therefore highly dependent on the stakeholder's selection and method used to aggregate their results.

Overall, it can be concluded, that AHP is a tool that can be potentially used in the process of an unbiased refrigerant selection process.

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