ХОЛОДИЛЬНА ТЕХНІКА

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Smart working fluid selection in refrigeration systems

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The choice of trade-off working fluid in the reverse Rankine cycle was studied as a problem of fuzzy optimization. Three main criteria were chosen as objective functions: thermodynamic (COP – coefficient of performance), economic (LCC – cost of life cycle) and ecological (GWP - global warming potential). The control variables (X) were considered as information characteristics of the working fluid. Critical parameters and a normal boiling point represented the latter. A sustainable solution that implements a compromise between the criteria based on information technology, defines a "smart" working fluid. The local criteria were expressed through the thermodynamic properties restored from the information characteristics of the working fluid X. The life cycle cost of the refrigeration system was calculated according to standard economic ratios. GWP values were selected from the refrigerant database. The class of substances considered is represented by possible alternative refrigerants for replacing R410A.

Keywords: *Refrigeration Systems; Energy Efficiency; Smart working fluid*

Розумний вибір робочих тіл в холодильних системах

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Вибір компромісних робочих тіл у зворотному циклі Ренкіна вивчали як задачу нечіткої оптимізації. В якості цільових функцій обрані три основні критерії: термодинамічний (коефіцієнт перетворення – COP), економічний (вартість життєвого циклу – LCC) і екологічний (глобальний потенціал потепління – GWP). Змінні управління (X) розглядали в якості інформаційних характеристик робочого тіла. Останні були представлені критичними параметрами і нормальною температурою кипіння. Узгоджене рішення, яке здійснює компроміс між критеріями на основі інформаційних технологій, визначає «smart - розумне» робоче тіло. Локальні критерії обчислювали через термодинамічні властивості, що відновлюються з інформаційних характеристик робочого тіла X. Вартість життєвого циклу холодильної системи, розраховували за стандартними економічним співвідношенням. Значення GWP вибирали з бази даних холодоагентів Клас розглянутих речовин представлений можливими альтернативними холодоагентами для замін R410A.

Ключові слова: *Холодильні системи; Енергоефективність; «Розумні» робочі тіла*

Nomenclature

COP	Coefficient of performance
CD	Compressor displacement
DB	Database
G	Constraints
GWP	Global warming potential
K	Vector criterion
K_i	Local criterion
K_C	Compromise criterion
$\boldsymbol{K_F}$	Flammability index
LCC	Life Cycle Cost
ODP	Ozone depletion potential
$\boldsymbol{P_r}$	Condenser/evaporator pressure ratio
$\boldsymbol{q_0}$	Net refrigerating effect

1 Introduction

Correct definition of the efficiency criteria determines the quality level design of the refrigeration system. Usually, three general goals (economic, environmental and thermodynamic).are considered in the design process: The best engineering solution corresponds to a compromise between these criteria and reflects a sustainability of decisions. The conventional thermoeconomic analysis introduces exergetic or exergoenvironmental costs to normalize different units. The implicit assumption about concordance of economic and energetic goals is a weak point of this suggestion in contrary to the real situation. Design goals contradict each other and impossible to find solution, which simultaneously satisfies all criteria.

Analysis of this ill-structured situation should include uncertainty notion.

The selection of working fluids with desirable combination of such properties as thermodynamic behavior, performance specifications, contribution to greenhouse effect, toxicity, flammability, and the others is one of the most important stages in design processes. Working fluid search requires applying molecular theory, experimental studies and engineering experience [1] - [4]. Of course, a working fluid that satisfies all desirable properties does not exist. However, the searching of a tailored working fluid with desirable properties set is possible to formulate on the base of the multi-criteria decision-making approach.

There are many criteria of efficiency of refrigeration system and the extreme values are desirable to reach for each ones taken separately. The integrated criterion is represented for the whole system by the vector ***K*,** including the local criteria ***Ki*** as the components.

The aim of present work is to include information technology (IT) based on a fuzzy logic approach in order to meet thermodynamic, economic, and environmental goals for working fluid selection in the reverse vapor compression cycles. The working fluid selection has been considered as a fuzzy nonlinear programming problem where local criteria: maximum energy (exergy) efficiency and minimum total cost rate as well as different environmental constraints in an ill-structured situation were represented by the fuzzy sets [5], [6]. The search of trade-off or the Pareto domain, where the value of thermodynamic criterion cannot be improved without the value of economic (or/and ecologic) criterion to be worsened, has been considered as a first step of the selection strategy. The concept of “smart” working fluid is introduced to reach a compromise among desired thermodynamic, environmental, economic, and social requirements and constraints. A possible definition for smart working fluid might be working fluid that uses surrounding environmental (exogenic) information to provide the desired thermodynamic, environmental, and economic criteria and constraints to its users. Other statements might define it as refrigeration systems that use smart working fluids that integrates latest IT technology to provide remote access to different refrigeration units.

2. Smart working fluid concept

We consider here only such criteria, which are linked by certain relations ***R*** to the properties of working fluids ***P***, i.e. the system defined by a three-tuple { ***K*, *R*, *P*** }. The relation ***R*** is a kind of technological operator and its structure can be determined via the equations of mass, momentum and energy balance, supplemented with the characteristic equation of state. It is usually impossible to estimate the performance attributes of refrigeration system from target properties (physical, chemical, ecological, etc.) correlated with molecular structure following to fundamental principles only. Therefore, we need to enlist restricted experimental information to define real properties ***P*** via their model properties ***M (X)***. The set of model parameters ***X*** as a mapping of the experimental data containing the observed properties ***P*,** gains in importance as *information characteristics* of working fluid by which its property behavior is restored. Physical meaning is important for the vector ***X*** and maps the working fluid molecular characteristics to select a proper configuration of molecule. The working fluid selection problem is formulated as the multi-criteria optimization problem: to find

$$\boldsymbol{Opt\,K}\,[K_1\,(X),\,K_2(X),\,\dots,\,Kn(X)],\ X\in X_P \qquad (1)$$

We assume that $K_j(X) = \|\, P_j,\ M_j(X)\,\|$ is a "distance" between the desired (ideal) efficiency of system $\boldsymbol{P_j}$ and its real model $\boldsymbol{M_j}$. Solution of multicriteria problem is a finding of compromise among all criteria and constraints and is formulated as follows: to construct the integrated function ***K*** as intersection of local criteria K_j

$$\boldsymbol{K} = K_1 \bigcap K_2 \bigcap \ldots \bigcap K_n\,. \qquad (2)$$

The formal solution of problem is added up to determination of the trade-off vector $\boldsymbol{X_{opt}}$ of such kind that $|\boldsymbol{K}\ (\boldsymbol{X_{opt}}\ )| \succ |\boldsymbol{K}\ (\boldsymbol{X})|$ for any $\boldsymbol{X} \neq \boldsymbol{X_{opt}}$ where $\succ$ is preference sign. In our case, the model parameters ***Xopt*** the presence of which requires the intellectual intervention of a person who makes decisions identify working medium having the desired complex of properties (*"smart" working fluid*). Critical parameters of substances are typical examples of the information characteristics of working fluid linked with its molecular structure.

To identify a molecular structure of corresponding real working fluid it is possible:

organize a direct search of substance in the critical property database (DB) with selection criterion

$$\{\left|1-T_c^{opt}/T_c^{DB}\right|+\left|1-P_c^{opt}/P_c^{DB}\right|+\left|1-V_c^{opt}/V_c^{DB}\right|\}\rightarrow min \qquad (3)$$

find a solution of inverse “structure – critical property” relationship problem.

The choice of appropriate technique to predict critical properties from molecular structure depends on the statement problem and it corresponds the final aim of molecular design.

3. Uncertainty in working fluid selection

Conventional thermoeconomic analysis is an example of lop-sided vision of multicriteria making-decision problem where only single set of control variables, strongly depended on decision maker experience, is recommended. Here we are trying to develop a flexible model of analysis taking into consideration a multicriteria nature of making-decision process and to minimize the uncertainties arising from different sources in the design of refrigeration systems.

The search of working fluid control variables ***X*** is formulated as a fuzzy nonlinear programming problem with ***n*** non-compatible criteria (economic, environmental, and thermodynamic), ***m*** decision variables, and ***k*** nonlinear constraints:

$$\boldsymbol{Optimize}\ \ \boldsymbol{K}\,[K_{th}(X),\,K_{ec}(X),\,K_{en}(X)] \qquad (4)$$

subject to

$$G_{Li} \le G_i\,(\mathbf{X}) \le G_{Ui}\,,\ I = 1,2,\dots,\mathbf{k} \qquad (5)$$

$$X_{Li} \le X_i \le X_{Ui}\,,\ i = 1,2,\dots,\mathbf{m} \qquad (6)$$

where $K_{th}(X)$, $K_{ec}(X)$, $K_{en}(X)$ represent the fuzzy local criteria of thermodynamic, economic, and environmental efficiency; X $(X_1, X_2, \dots, X_m)$ is a vector of control variables; G_{Li}, G_{Ui}, are respectively the lower and upper limits for the constraints $G_i(X)$ and x_{Li}, x_{Ui} are respectively the lower and upper bounds for the control variables.

There are several methods of finding “good” solutions to the above problem based on scalar optimization. However, as example, the attempts to resolve the CGAM problem [7] via single objective paradigm illustrate a conflict among different approaches and lack of compromise decision. Multicriteria approach is based on synergetic combination of formal and informal making-decision procedures to select a trade-off solution of problem. There are no entirely formal mathematical tools to resolve a multicriteria problem and additional exogenous information is needed.

In the present study, a next sequence of decision-making steps in fuzzy thermoeconomic analysis of refrigeration system is applied [8].

– Determination of the Pareto optimal (or compromise, or trade-off) set X_P as the formal solution of multicriteria problem to minimize a conflict source of uncertainty;

– Fuzzification of goals as well as constraints to represent an ill-structured situation;

– Informal selection of convolution scheme to switch over a vector criterion $K[K_{th}(X)\ K_{ec}(X), K_{en}(X);]$ into scalar combination of the $K_{th}(X)$, $K_{ec}(X)$, and $K_{en}(X)$;

– Evaluation of the final decision vector $X_{opt} \in X_P$ to minimize a vagueness source of uncertainty.

4. Pareto optimum set

The Pareto optimality paradigm [9] is a formal solution of multicriteria problem where the value of one of the local criteria cannot be improved without the values of the others to be worsened. Geometrical interpretation of the Pareto set (**AB**-line) for the case of two criteria and two decision variables is given in Fig.1.

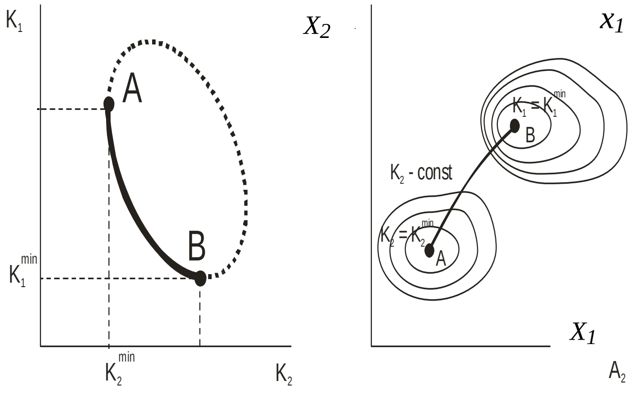

Figure 1 – 2D - Pareto set in criteria ($K_1 - K_2$) and control variable ($x_1 - x_2$) spaces

Here $K_1^{\min}$ is interpreted as a minimum deviation of thermodynamic efficiency model from ideal solution (e.g., exergetic efficiency $K_{th} = 1$ is an example of “ideal” solution), $K_2^{\min}$ is a minimum of economic efficiency model (e.g., the minimum of the cost objective function). The best result from the thermodynamic reasons usually corresponds to the worst decision for economic consideration. It is obvious this assumption is wide of the mark and direct calculations of the Pareto set confirm this fact.

There are several methods of finding the Pareto set. Let us assume that we compare two obtained solutions, X^* and X_0, for which holds the inequality:

$$K(X_0) \le K(X^*) \qquad (7)$$

The approximate construction of the Pareto set is referred to the sphere of insufficiently explored problems in thermal and refrigeration system design and usually it is reduced to the solution of the sequence of the mathematical programming problems [10] or application of evolutionary multi-objective optimization technique [11].

The main defect of these methods is an impossibility to find the multiple solutions and heuristic nature of K_i^0 boundary guessing. The same defects accompany the weighting methods, which are playing a central role in the theory of multi-objective optimality. There are several methods available in the literature for solving multi-objective optimization problems as mathematical programming models, via *goal programming*, *weighted sum method*, *goals as requirement*, *goal attainment,* and the *iso-resource-cost solution* methods. Strengths and weakness of these methods are described in literature [12].

Recently, *evolutionary algorithms* were found useful for solving multicriteria problems. Evolutionary algorithms have some advantages over traditional mathematical programming techniques. At present time, there is no well-accepted method of the Pareto set determination that will produce an appropriate set of solutions for all problems. This motivates the further development of reliable approaches to multicriteria problem. The alternate normal-boundary intersection (NBI) method for generating of the Pareto surface was proposed by Das, Dennis [13].

In the Pareto domain, there is no single solution, but rather a set of alternative solutions. The Pareto-optimality should be regarded as a tool for generating alternatives from which decision maker can select the final decision.

5. Convolution methods

Crisp convolution. The next step consists in determination of the final parameter set from the Pareto set using additional exogenous information and reducing the vector criterion to a scalar one. This step is in a fact the problem of d[illegible]naking and cannot be entirely formalized. Th[illegible] many approaches how a vector criterion can be transformed into a scalar criterion.

A general concept as origin of the final decision that satisfies the Pareto ranking is based on the striving for uncertainty minimization. Two basic tendencies (isolationistic and cooperative) usually are considered to aggregate a vector of local criteria into global (or generalized) scalar criterion. The isolationistic convolution schemes are additive (global criterion is represented as a weighted sum of local criteria) and entropic (global criterion is represented as a sum of local criterion logarithms). If behaviour of each criterion is complied with common decision to minimize some general (cooperative) criterion then a convolution scheme can be presented in the form

$$K_C(X)=\underset{\boldsymbol{X\in X_P}}{min}\lfloor w_i(K_i(X)-K_i^0)\rfloor,\qquad 1\le i\le n,\quad (8)$$

where w_i are the weight coefficients, K_i^0 - an infimum of desired result (the ideal point) that is acceptable for decision maker remaining in the coalition, K_C is a global trade off criterion. If it is possible to come to an agreement about preference (weight) for each criterion then final decision can be found as the solution of scalar non-linear programming problem:

$$K_C(X)=\min\sum_{i=1}^{n}\left|w_i(K_i(X)-K_i^0)\right|\ ,\quad \boldsymbol{X\in X_P}\quad (9)$$

If no concordance among decision makers concerning of weight choice then arbitration network is preferable. Classical arbitration scheme was derived mathematically rigorously by Nash but very often criticized from common sense:

$$K_C(X)=\min\prod_{i=1}^{n}\left|K_i(X)-K_i^0\right|,\quad \boldsymbol{X\in X_P}\qquad (10)$$

All crisp convolution schemes under discussion try to reduce an uncertainty deriving from conflict among different criteria in the Pareto domain. The next step is extenuation of uncertainty driving from vagueness.

Fuzzy convolution scheme

The theory of fuzzy sets was put forward by Zadeh [6] with explicit reference to the vagueness of natural language, when describing quantitative or qualitative goals of system. Here we assume that local criteria: maximum thermodynamic efficiency (or minimum deviation of real thermodynamic efficiency from ideal one) and maximum profit per unit of production (or minimum total cost rate) as well as different constraints in an ill-structured situation can be represented by fuzzy sets.

A final decision is defined by the Bellman and Zadeh [14] model as the intersection of all fuzzy criteria and constraints. The membership function of the objectives and constraints can be chosen linear or nonlinear depending on the context of problem. One of possible fuzzy convolution schemes is presented below.

– Initial approximation ***X***-vector is chosen. Maximum (minimum) values for each criterion K_i are established via scalar maximization (minimization). Results are denoted as "ideal" points { X_j^0 , $j = 1...m$ }

– The matrix table [*T*], where the diagonal elements are "ideal" points, is defined as follows:

$$[T]=\begin{bmatrix} K_1(X_1^0) & K_2(X_1^0)... & K_n(X_1^0)\\ K_1(X_2^0) & K_2(X_2^0)... & K_n(X_2^0)\\ : & : & :\\ K_1(X_m^0) & K_2(X_m^0)... & K_n(X_m^0)\end{bmatrix}\quad (11)$$

– Maximum and minimum bounds for criteria are defined:

$$\begin{aligned}K_i^{\min}&=\min_j K_j(X_j^0)=K_i(X_i^0),\ i=1...n;\\ K_i^{\max}&=\max_j K_j(X_j^0),\ \ i=1...n.\end{aligned}\quad (12)$$

– The membership functions are assumed for all fuzzy goals as follows

$$\mu_{Ki}(X)=\begin{cases}0, & if\ \ K_i(X)>K_i^{max}\\ \dfrac{K_i^{max}-K_i}{K_i^{max}-K_i^{min}} & if\ \ K_i^{min}<K_i\ \le K_i^{max},\\ 1, & if\ \ K_i(X)\le K_i^{min}\end{cases}\quad (13)$$

– Fuzzy constraints are formulated:

$$G_j(X)\le G_j^{max}+d_j,\quad j=1,2,...k\quad (14)$$

where d_j is a subjective parameter that denotes a distance of admissible displacement for the bound G_j^{max} of the *j*-constraint. Corresponding membership functions are defined in following manner:

$$\mu_{Gj}(X)=\begin{cases}0, & if\ \ G_j(X)>G_j^{max}\\ 1-\dfrac{G_j(X)-G_i^{max}}{d_j} & if\ \ G_j^{max}<G_j(X)\le G_j^{max}+d_j,\\ 1, & if\ \ G_j(X)\le G_j^{max}\end{cases}\quad (15)$$

– A final decision is determined as the intersection of all fuzzy criteria and constraints represented by its membership functions. This problem is reduced to the standard nonlinear programming problem

$$\begin{aligned}\lambda&\le\mu_{Ki}(X),\quad i=1,2,...,n;\\ \lambda&\le\mu_{Gj}(X),\quad j=1,2,...,k\end{aligned}\quad (16)$$

The solution of the multicriteria problem discloses the meaning of the optimality operator (1) and depends on the decision maker experience and understanding problem.

6. Results and discussion

Replacement of artificial refrigerants that are incompatible with Nature can be eliminate or block a pathway of ozone harmful substances to biosphere. The accuracy of prognosis for experimentally observable thermodynamic and design characteristics narrows the area of search in the space of competitive economic, environmental and technological criteria.

Here we consider the operation of refrigeration system, which is simulated by the reverse Rankine cycle. The main processes in the single-stage vapor compression cycle include isentropic compression, isobaric cooling + condensation + subcooling, throttling, and isobaric cooling + evaporation + superheating.

The following design specifications are chosen: evaporator and condenser temperatures, $T^0_{\mathrm{ev}} = -10$ °C, $T^0_{\mathrm{cond}} = 35$ °C net refrigerating effect – $\boldsymbol{q}_0^0$ and condenser/ evaporator pressure ratio – $\boldsymbol{P}_r < 10$. The entire set of design indices includes: *thermodynamic* (specific refrigerating effect, volumetric capacity, specific adiabatic work, condenser/evaporator pressure ratio, coefficient of performance, adiabatic power), *economic* (life cycle cost), and *environmental* (flammability index and *GWP)* criteria. Constraint for environmental criterion is chosen as *GWP* < 400.

Thermodynamic properties of working fluids and appropriate design specifications are simulated by the one-fluid Peng-Robinson [17] model of EoS**.** Database for critical parameters of concurrent refrigerants was chosen from [16,18]. ***LCC*** calculations have been provided by algorithms from [19].

Multi-criteria comparative analysis algorithm is realized by the following way:

– Thermodynamic properties and design characteristics of vapor compression cycle are calculated for specified external conditions.

– The “ideal” indexes K_i^0 are presented by the vector criterion $\boldsymbol{K}$ which is calculated via thermodynamic properties.

– The membership functions μ_i for each thermodynamic and economic index are defined by relations (11) – (15).

– The integrated criterion of refrigerant selection is written in the C-metrics form

$$K_C = \sum_{i=1}^{N} |\mu_i| \qquad (17)$$

– Minimum value of KC - criterion corresponds to smart refrigerant among competitive working fluids.

Results of comparison for refrigerants from database [18] have been demonstrated a lack of environmentally appropriate substance with *GWP* < 400 as replacement candidature. e trade-off values of the decision variables *Xopt* as a result of the fuzzy optimization were obtained by the direct enumeration of information characteristics for all substances from the refrigerant database and consequent ranking of their membership numbers lC.

We have been able to identify five potentially azeotropic and four near azeotropic substitutes for R410A, all formed from natural refrigerants or synthetic chemicals with a global warming potential (GWP) less than 150. There are significant environmental problems associated with prevalent refrigerant R32, most notable a GWP of 650, which exceeds the EU F- gas regulation threshold of 150 by a considerable margin.

7. Conclusions

We would therefore conclude that a near azeotropic blend of R1270, propene / R161, ethyl fluoride, an azeotropic blends of Hydrogen Sulphide / R290, Propane and R717, ammonia / R170, ethane all have potential as substitutes for R410A. Of these, we would hope to achieve a safety classification in accordance with ASHRAE 34 of A2 for the R1270 / R161 near azeotrope, but B3 for hydrogen sulphide / propane and ammonia / ethane [20].

R410A has a bubble / dew point of 221.55K, whereas the figures for our near azeotropes are:

R161, ethyl fluoride and CF_3I, methyl iodide $T_{bubble} = 241.75$ $T_{dew} = 244.27$;

R1270, propene / R161, ethyl fluoride $T_{bubble} = 228.84$ $T_{dew} = 230.37$;

R744, Carbon Dioxide / R41, methyl fluoride $T_{bubble} = 188.63$ $T_{dew} = 190.40$.

Moreover, from the table below, it can be seen that of our five azeotropes two appear to suitable as direct substitutes for R410A.

	Mixtures	Azeotropy membership	P_{dew}, kPa T = -10°C	$P_{bubbl,}$ kPa T = -10°C
	R410A	A	544.7	550.5
1	R170, ethane / R41, methyl fluoride	**A**	1912	1912
2	R744, Carbon Dioxide / R170, ethane	**A**	2888	3003
3	R717, ammonia / R170, ethane	**A**	593.4	**?**
4	Hydrogen Sulphide / R290, Propane	**A**	537.2	658.4
5	Hydrogen Sulphide / R1270, Propene	**A**	648.8	736.1

? *More detailed analysis is required*

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This study is one of first attempts to apply methodology of smart working fluid for the reverse Rankine cycle. Fuzzy set is prospective tool to seek compromise among energy efficiency, environmental constraints and economic indices in conceptual design of refrigeration systems. However, no pure substances still were found that could replace refrigerants non-compatible with Nature with targeted cooling capacity and GWP < 400.

The possible way to solve this problem is application of high-efficiency natural fluids (e.g., hydrocarbons) which are doubtful in terms of security. Other opportunity is to offer mixture compatible with nature: to reduce hazard from use a new family of alternative refrigerants that have nonzero greenhouse effect and unknown damage potentials for environment in future via design of mixtures of natural and alternative refrigerant components, i.e. *naturalization of alternative refrigerants* .

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