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FUZZY THERMOECONOMIC APPROACH TO NANOFLUID SELECTION IN VAPOR COMPRESSION REFRIGERATION CYCLE

*The working fluid selection in the vapour compression refrigeration cycles has been studied as a fuzzy thermoeconomic optimization problem. Three criteria: thermodynamic (**COP** Coefficient Of Performance), economic (**LCC** Life Cycle Cost), and ecologic (**GWP –** Global Warming Potential) are chosen as target functions. The decision variables **X** as an information characteristics of desired refrigerant are presented by its critical parameters and normal boiling temperature. Local criteria are expressed via thermodynamic properties restored from information characteristics of refrigerant **X**, as well as life cycle costs are calculated by the standard economic relationships. **GWP** values are taken from the refrigerant database. Class of substances under consideration is presented by the natural refrigerant R600a embedded with nanostructured materials.*

Keywords: *Thermoeconomics – Fuzzy Set – Refrigerant Selection – Reverse Cycle – Nanostructured materials –– Nanofluids*

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НЕЧІТКИЙ ТЕРМОЕКОНОМІЧНИЙ ПІДХІД ДО ВИБОРУ НАНОФЛЮЇДІВ В ПАРОКОМПРЕСІЙНИХ ХОЛОДИЛЬНИХ ЦИКЛАХ

Завдання вибору робочих *середовищ для холодильних парокомпресійних циклів розглянуто як задача нечіткої термоекономічної оптимізації. В якості цільових функцій розглядали три критерії: термодинамічний (коефіцієнт термотрансформації), економічний (ціна життєвого циклу) і екологічний (потенціал глобального потепління). Параметри управління X (інформаційні характеристики холодоагенту) представлені критичними параметрами і нормальною температурою кипіння. Локальні критерії виражені через термодинамічні властивості, що відновлені з інформаційних характеристик холодоагенту. Ціна життєвого циклу розраховується за стандартними економічними співвідношеннями. Значення потенціалу глобального потепління взяті з бази даних для холодоагентів. Клас розглянутих речовин представлено природним холодоагентом R600a з добавками наноструктурованих матеріалів.*

Ключові слова: *Термоекономіка - Нечітка множина - Вибір холодоагенту - Зворотний цикл - Наноструктурні матеріали - Нанофлюїди*

I. INTRODUCTION

The selection of refrigerants with desirable combination of such properties as contribution to greenhouse effect, flammability, toxicity, thermodynamic behavior, performance specifications, and the others is one of the most important stages in simulation and design of refrigeration processes. Refrigerant selection problem has been tackled using achievements of molecular theory, engineering experience and experimental studies [1] - [4]. Selection strategy is an inverse engineering problem of incorporating property and technological performances directly into the design of the refrigeration devices. Clearly, a refrigerant that combines all the desirable properties and has no undesirable properties does not exist. However, algorithms for searching of a “tailored” refrigerant with desirable combination of properties are able to formulate mathematically on the basis 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. Usually, three main goals are involved in the design process: thermodynamic, economic and environmental. The generalized efficiency criterion is represented for the whole system by the vector $\boldsymbol{K}$, including the local criteria $\boldsymbol{Ki}$ as the components and mapping the multitude of requirements imposed on refrigeration system. The attainment of optimum solution corresponds to a compromise between different criteria and reflects a sustainability of engineering decisions. Various methodologies have been suggested to find a compromise between thermodynamic and economic criteria for local criteria aggregation into single objective function.

The aim of present study is to introduce the fuzzy set methodology in order to meet thermodynamic, economic, and environmental goals for selection of refrigerants embedded with nanostructured materials. Thermoeconomic optimization 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. The Bellman - Zadeh model as the intersection of all fuzzy criteria and constraints has been used for a final decision-making.

II. TAILORED REFRIGERANT CONCEPT

We consider here only such criteria, which are linked by certain relations $\boldsymbol{R}$ to the properties of working fluids $\boldsymbol{P}$, i.e. the system defined by a three-tuple $\{\boldsymbol{K}, \boldsymbol{R}, \boldsymbol{P}\}$. The relation $\boldsymbol{R}$ 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. So, we need to enlist restricted experimental information to define real properties $\boldsymbol{P}$ via their model properties $\boldsymbol{M}(\boldsymbol{X})$. The set of model parameters $\boldsymbol{X}$, as a mapping of the experimental data containing the observed properties $\boldsymbol{P}$, gains in importance as *information characteristics* of substance by which its property behavior can be restored. A physical meaning is no less important for the vector $\boldsymbol{X}$ and should map the working fluid characteristics on the molecular level to select a proper molecular configuration. The refrigerant selection problem can be mathematically formulated as the following multi-criteria optimization problem: to find

$$\textbf{\textit{Opt}}\ \boldsymbol{K}\,[K_1(\boldsymbol{X}), K_2(\boldsymbol{X}), \dots, K n(\boldsymbol{X})],\ \boldsymbol{X} \in \boldsymbol{X}_P \qquad (1)$$

We assume that $K_j(X) = \| \boldsymbol{P}_j, M_j(\boldsymbol{X}) \|$ is a "distance" between the desired (ideal) efficiency of system $\boldsymbol{P}_j$ and its real model $\boldsymbol{M}_j$. For thermodynamic criterion, K_{th} the value $\boldsymbol{P}_j$ corresponds to the theoretical maximum of the objective function, e.g. efficiency of the Carnot cycle. Solution of multicriteria problem is a finding of compromise among all criteria and constraints and can be formulated as follows: to construct the function

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

The formal solution of problem is added up to determination of the optimum 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. The model parameters $\boldsymbol{X}_{opt}$ identify a trade-off decision possessing to desired efficiency criteria. In our case the model parameters $\boldsymbol{Xopt}$ identify an optimum working medium having the desired complex of properties ("*tailored" refrigerant*). Critical parameters of refrigerants are typical examples of the information characteristics of substance linked with its molecular structure.

III. UNCERTAINTY IN MULTICRITERIA MAKING DECISION

Here we attempt to develop a flexible model of thermoeconomic 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 unit.

Thermoeconomic optimization problem is formulated as a fuzzy nonlinear programming problem with $\boldsymbol{n}$ non-compatible criteria (economic, environmental, and thermodynamic), $\boldsymbol{m}$ decision variables, and $\boldsymbol{k}$ nonlinear constraints:

$$\textbf{\textit{Optimize}}\ \boldsymbol{K}\,[K_{th}(\boldsymbol{X}), K_{ec}(\boldsymbol{X}), K_{en}(\boldsymbol{X})] \qquad (3)$$

subject to

$$G_{Li} \le G_i\,(\boldsymbol{X}) \le G_{Ui}\,,\ I = 1,2,\dots,\boldsymbol{k} \qquad (4)$$

$$X_{Li} \le X_i \le X_{Ui}\,,\ i = 1,2,\dots,\boldsymbol{m} \qquad (5)$$

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

IV. CONVOLUTION SCHEMES

Crisp convolution schemes. 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 decision-making and cannot be entirely formalized. There are 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

$$K_C(X) = \min\lfloor w_i(K_i(X) - K_i^0)\rfloor,\ 1 \le i \le n,\ \boldsymbol{X \in X_P} \quad (6)$$

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 on preference (weight) for each criterion then final decision can be found as the solution of scalar non-linear programming problem:

$$K_C(X) = \min \sum_{i=1}^{n} \left| w_i(K_i(X) - K_i^0) \right|,\ \boldsymbol{X \in X_P} \quad (7)$$

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:

$$K_C(X) = \min \prod_{i=1}^{n} \left| K_i(X) - K_i^0 \right|,\ \boldsymbol{X \in X_P} \quad (8)$$

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 [5] 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 [6] model as the intersection of all fuzzy criteria and constraints and is represented by its membership function $\boldsymbol{\mu(X)}$ as follows:

$$\mu_K(X) = \mu_{Kth}(X) \cap \mu_{Kec}(X) \cap \mu_{Ken}(X) \cap \mu_{Gi}(X)).$$

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 $\boldsymbol{X}$-vector is chosen. Maximum (minimum) values for each criterion K_i are established via scalar maximization (minimization). Results are denoted as "ideal" points $\{ X_j^0\ , j = 1 \ldots m\}$
- The matrix table $[T]$, where the diagonal elements are "ideal" points, is defined as follows:

$$[T] = \begin{bmatrix} K_1(X_1^0) & K_2(X_1^0)\ldots & K_n(X_1^0) \\ K_1(X_2^0) & K_2(X_2^0)\ldots & K_n(X_2^0) \\ : & : & : \\ K_1(X_m^0) & K_2(X_m^0)\ldots & K_n(X_m^0) \end{bmatrix} \quad (9)$$

- Maximum and minimum bounds for criteria are defined:

$$\begin{aligned} K_i^{\min} &= \min_j K_j(X_j^0) = K_i(X_i^0),\ i = 1..n; \\ K_i^{\max} &= \max_j K_j(X_j^0),\ i = 1..n. \end{aligned} \quad (10)$$

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

$$\mu_{Ki}(X) = \begin{cases} 0, & if\ \ K_i(X) > K_i^{\max} \\ \dfrac{K_i^{\max} - K_i}{K_i^{\max} - K_i^{\min}} & if\ \ K_i^{\min} < K_i \le K_i^{\max}, \\ 1, & if\ \ K_i(X) \le K_i^{\min} \end{cases} \quad (11)$$

- Fuzzy constraints are formulated:

$$G_j(X) \le G_j^{\max} + d_j,\quad j = 1, 2, ..k \quad (12)$$

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:

$$\mu_{Gj}(X) = \begin{cases} 0, & if\ \ G_j(X) > G_j^{max} \\ 1 - \dfrac{G_j(X) - G_i^{max}}{d_j} & if\ \ G_j^{max} < G_j(X) \le G_j^{max} + d_j, \\ 1, & if\ \ G_j(X) \le G_j^{max} \end{cases} \quad (13)$$

- 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 problems: to find the such values $\boldsymbol{X}$ and λ that maximizes λ subject to

$$\begin{aligned} \lambda &\le \mu_{Ki}(X),\quad i = 1, 2, \ldots, n; \\ \lambda &\le \mu_{Gj}(X),\quad j = 1, 2, \ldots, k \end{aligned} \quad (14)$$

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

V. 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. Here we consider the operation of refrigeration system which is simulated by the reverse Rankine cycle. The reference refrigerant isobutene R600a was chosen.

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, $T_{ev}^0 = -10^o C, T_{cond}^0 = 35^o C$; net refrigerating effect - $\boldsymbol{q}_0^0$ and condenser/evaporator pressure ratio – $\boldsymbol{P_r} < 10$. The entire set of design indices includes: *economic* (life cycle cost), *thermodynamic* (specific refrigerating effect, volumetric capacity, specific adiabatic work, condenser/evaporator pressure ratio, coefficient of performance, adiabatic power), and *environmental* (flammability index and *GWP)* criteria. Constraint for environmental criterion is chosen as GWP < 400. ***LCC*** calculations have been provided by algorithms from [7].

To apply fuzzy thermoeconomic approach the effect of nanoparticle doping on the coefficient of performance (COP) is studied. We suggest the fluids with small impurities obey the corresponding state principle. It is hypothesized that the regular and singular parts of thermodynamic surface of base fluid and nanofluid with small nanoparticle volume concentration are coincided in reduced form. To predict the critical point shift of pure substances at nanostructured materials adding the thermodynamic models are used and influence of nanoparticle size and geometry is studied. The equations of state for nanofluids are presented and thermodynamic properties are calculated on the similarity theory base. The search algorithm of nanofluid critical parameters is as follows. The compressibility factor (*Z*) of nanofluid is defined via scaled pure reference fluid properties. To estimate the critical parameters of nanofluid the fundamental equations of state in reduced form for industrial fluids [8] are used.

Here we have considered the critical point shift for some low GWP refrigerants embedded with Al_2O_3, MnO_2, TiO_2, F_3O_4 nanoparticles. To compute thermodynamic properties of nanofluids in the range 0… 5% volume concentrations of nanoparticles the density of nanofluid calculated via reference fluid density by standard linear relationship. The critical parameters for nanofluids also give an opportunity to calculate their thermodynamic properties from the reduced EoS [8]. The change of thermodynamic properties due to the compressibility of the fluid with nanoparticles suspended is negligible in the low volume fraction limit.

The direct assessment of the efficiency criteria for the reverse Rankine cycle via artificial neural networks (ANN) approach is used. The construction of ANN includes the following sequence of actions: a choice of initial data for training; a choice of architecture of a network; dialogue selection of ANN parameters; process of training; check of adequacy of training (validation); and forecasting. Output values in the initial sample were calculated for Al_2O_3, MnO_2, F_3O_4 nanoparticles based on thermodynamic properties. As input values the given T_C, P_C and T_B are used. The various architectures of neural networks with different neuron numbers and activation functions in the first and second layers were considered. The forecast of efficiency criteria for the reverse Rankine cycle as output parameters which describe the coefficient of performance with high accuracy and without thermodynamic property calculations is given.

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 best value of design characteristics K_i^0 is chosen for each criterion among all concurrent refrigerants. The “ideal” indexes K_i^0 are presented by the vector criterion ***K*** which is calculated via thermodynamic properties.
- The membership functions μ_i for each thermodynamic and economic index are defined by relations (10) – (14). Environmental criteria cannot be expressed by direct way via information characteristics in the terms of critical parameters of substances.
- The thermoeconomic criterion of refrigerant selection is written in the C-metrics form

$$K_C = \sum_{i=1}^{N} \left|\mu_i\right| \qquad (15)$$

- Minimum value of $\boldsymbol{K_C}$ - criterion corresponds to best refrigerant among competitive working fluids from thermoeconomic point of view. A final decision takes into account a ranking of the environmental criteria also.

The final result corresponds the next preference chain of trade off efficiency nanorefrigerants based on reference R600a fluid: Al_2O_3, TiO_2 , MnO_2, F_3O_4.

VI. CONCLUSIONS

Fuzzy thermoeconomic analysis is powerful tool to finding of compromise among energy efficiency, environmental constraints and economic indices of working media in conceptual design of refrigeration systems. This study is one of first attempts to apply methodology of tailored working fluid design to selecting optimum nanoparticle doping for reverse cycles. Present calculations demonstrate the best additives to R600a are Al_2O_3 nanoparticles that have thermodynamic and economic items.

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
LCC	Life Cycle Cost
ODP	Ozone depletion potential
$\boldsymbol{P_r}$	Condenser/evaporator pressure ratio
$\boldsymbol{q_0}$	Net refrigerating effect
T	Temperature (K)
X	Decision variables
w	Weight coefficient

	Subscripts
c	critical
cond	condenser
ec	economic
en	environmental
opt	optimum
th	thermodynamic
μ	membership function

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НЕЧЕТКИЙ ТЕРМОЭКОНОМИЧЕСКИЙ ПОДХОД К ВЫБОРУ НАНОФЛЮИДОВ В ПАРОКОМПРЕССИОННЫХ ХОЛОДИЛЬНЫХ ЦИКЛАХ

Задача выбора рабочих сред в холодильных парокомпрессионных циклах рассмотрена как нечеткая задача термоэкономической оптимизации. В качестве целевых функций выбирали три критерия: термодинамический (коэффициент термотрансформации), экономический (цена жизненного цикла) и экологический (потенциал глобального потепления). Параметры управления X (информационные характеристики хладагента) представлены критическими параметрами и нормальной температурой кипения. Локальные критерии выражены через термодинамические свойства, восстановленные по информационным характеристикам хладагента X. Цена жизненного цикла рассчитывается по стандартным экономическим соотношениям. Значения потенциала глобального потепления взяты из базы данных для хладагентов. Класс рассматриваемых веществ представлен природным хладагентом R600a с добавками наноструктурированных материалов.

Ключевые слова: *Термоэкономика - Нечеткое множество - Выбор хладагента - Обратный цикл - Наноструктурные материалы - Нанофлюиды*

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