A new method of search design of refrigerating systems containing a liquid and gaseous working medium based on the graph model of the physical operating principle

A A Yakovlev, V S Sorokin, S N Mishustina, N V Proidakova, S G Postupaeva

Volgograd State Technical University, V I Lenin Ave., 28, Volgograd, 400131, Russia

E-mail: S.o.r.o.k.i.n@mail.ru

Abstract. The article describes a new method of search design of refrigerating systems, the basis of which is represented by a graph model of the physical operating principle based on thermodynamical description of physical processes. The mathematical model of the physical operating principle has been substantiated, and the basic abstract theorems relatively semantic load applied to nodes and edges of the graph have been represented. The necessity and the physical operating principle, sufficient for the given model and intended for the considered device class, were demonstrated by the example of a vapour-compression refrigerating plant. The example of obtaining a multitude of engineering solutions of a vapour-compression refrigerating plant has been considered.

1. Introduction

As of today, scientific and technological progress in many branches of industry is characterised by the advanced development of engineering devices compared to the methods of their creation. Traditional design is incapable to provide a radical reduction of the lead time and enhancement of devices. A growing interest to the methodology of design is promoted by the creation and evolvement of design methods and development of computer-aided design (CAD) of more new groups of engineering systems on their basis.

In connection with this, the aim of this research is to establish a scientific substantiated specialised method of the search design of engineering solutions of refrigerating systems (RS) containing a liquid and gaseous working medium allowing improvement of the quality and efficiency of designers’ labour engaged in their development at early stages of designing.

Implementation of similar ideas in the majority of familiar approaches is based on application of the graph models, which represent physical processes occurring in engineering systems [1]. Therefore, in order to achieve the set goal, it is necessary to solve the following problems: to develop a graph model of the physical operating principle (POP) for the considered class of engineering systems, to verify the adequacy of this model and to form the method of the synthesis of engineering solutions on the basis of the POP model.

2. An applied model of the physical operating principle

One of the most familiar and theoretically substantiated approaches is a function-physical method of
search design [2,3]. The POP model represented as an oriented graph underlies it. The nodes of such graph are physical objects providing transformation of input and output streams of substance, energy, signals, represented as edges.

Analysis of the physical processes implemented in RS has shown that this model requires substantial alignment, and in order to adequately represent POP of this class of devices, the semantic load of nodes and edges must be specified, and an opportunity of representing the displacement routes and the order of interaction of the working medium is provided.

The most prospective way of solving this task consists in the use of the conceptual apparatus of phenomenological thermodynamics [4,5]. This is conditioned by three reasons. First, thermodynamics embraces the whole totality of natural phenomena, which has made its apparatus maximally distinct and universal and, thus, providing the opportunities of using it for describing possible POP. Secondly, on the basis of engineering thermodynamics, the description of the operation of the majority of RS is established. This conditions the conventionality of its terminology when training specialists, designing these devices and facilitates their perception of this model. Third, thermodynamics allows a substitution of a complex real phenomenon for some conditional, elementary ones, which facilitates the process of formalization of POP description.

In the proposed model, the nodes designate the spots, so-called characteristic points, where the working medium of RS undergoes the interactions, for which a unified formula of an analytical expression of the generalised work is offered in thermodynamics:

\[ dQ = P \, dE, \quad (1) \]

where

- \( P \) – generalised force or an intensial which implies such physical values as force, velocity, pressure, absolute temperature, potential difference, chemical potential and etc.;
- \( E \) – a generalised coordinate or an extensor which implies such values as displacement, the number of movements, volume, entropy, electric charge, mass of a substance and others.

The semantics of edges is determined by the following considerations. Any interactions of the working medium are always connected with the changes of extensor \( E \), that is, they are conditionally compared to the process of transfer over the reference surface of the thermodynamical system of a certain amount of \( dE \). For each interaction, there is typical parameter \( E \) which defines explicitly physical properties of the working medium on a qualitative and quantitative side in as much as they are connected to the given interaction [6].

The interactions of the working medium are represented in the graph by edges with the designation of extensors conjugated with them. These edges are incident to those nodes (characteristic points) where corresponding interactions take place [7].

Besides, during an operation process, the substance of the working medium of RS can move inside of the plant, which conditions the necessity of introduction of edges of the second type – path ones connecting characteristic points.

For functioning of many RS, the periodicity of interactions and displacements of the working medium is typical. The examples are gaseous cryogenic machine operating by an inverse Stirling cycle, turborefrigeration machines and others. In this case, the POP graph is supplemented with a cyclogram for periodic interactions and displacements of the working medium.

When developing the POP model, the characteristic points of RS, a sequence and types of interactions in them, as well as the order of passing them by the working medium are determined. For all elements of the graph, the following symbols are introduced.

The nodes are marked by letter \( V \) with lower and upper indices. The indices indicate the state of the working medium and a serial number of the characteristic point, correspondingly. If the working medium is subsequently passes through several states in one characteristic point, it can have a compound designation consisting of several letters. Edges – interactions are designated by letter \( E \) with lower and upper indices which determine the sort of interaction and its series number. Edges – streams of the working medium are designated by letter \( I \), which has lower and upper indices as well, determining the components of the working medium and a series number of the edge.
3. Modelling physical operating principles of refrigerating systems

In order to substantiate the suggested model of POP for the considered class of devices, the POP models of the main types of modern refrigerating systems were built [8,9]. As an example, figure 1 shows the scheme of the vapour-compressive refrigerating plant, and figure 2 shows its POP model.

A stream of the liquid refrigerating medium enters evaporator 1 (nodes $v_1^1, v_1^2$), where it boils (process $e_1^{\text{phase}}$) owing to the warmth (process $e_1^{\text{therm}}$), taken from the cooling medium (TO), under constant lowered pressure and low temperature corresponding to this pressure. An evaporated refrigerant is sucked through steam dome 2 ($v_4^1$) into working chamber ($v_5^3$) of radial compressor 3 and is compressed ($e_2^{\text{mech}}$) up to high pressure [10].

The compressed and highly heated refrigerating medium in the state of dry saturated or overheated vapour is pumped into condenser 4 ($v_1^1, v_1^2$), through which a corresponding amount of colling water passes continuously (TP). The condensation process of ($e_1^{\text{phase}}$) of the refrigerating medium proceeds at constant pressure and temperature. The liquid refrigerating medium on the way to the evaporator passes through flow control valve 6 ($v_2^1, v_2^2$), where the thermodynamical process of strangling (crumpling) takes place. Passing through the narrowed section on the boundary between the area of high (condenser) and low (evaporator) pressures, the refrigerating medium partially boils ($e_2^{\text{phase}}$), expands nonuniformly ($e_1^{\text{mech}}$) and its pressure reduces. The strangling process is accompanied by the reduction in temperature ($e_2^{\text{therm}}$) of the refrigerant.

A part of the liquid refrigerant (streams $i_7^2, i_8^3$) is fed from condenser 4 to oil-to-oil exchanger 9 ($v_3^1, v_7^1$) for cooling of the oil in the compressor lubricating system. Another part of the liquid refrigerant is fed from the condenser (stream $i_6^2$) to cool electric motor 10. In this case, the return of the oil from the condenser and the evaporator into the lubricating system of the compressor owing to evaporation of the refrigerating medium.

The analysis conducted has completely justified the adequacy of the used model of POP for refrigerating systems. This model allows considering the sequence of displacement and interactions of the working medium in the space and in time and concentrates the designer’s attention on the peculiarities of physical processes which determine the RS morphology.

4. Synthesis of engineering solutions on the basis of the model of the physical operating principle

The method of synthesis of engineering solutions on the basis of the POP model represented in the form of the algorithm consisting of the set of procedures and conditions. For each procedure, the structures of input and output data in the form of relational tables were determined.

Each element of the model is connected with the construction functions revealed on the basis of the analysis of such abstractions of thermodynamics as a “thermodynamic system”, a “control surface”, “external” and “internal degrees of freedom”. A detailed description of these functions is given in works.

During development of the engineering solution with nodes and edges of the POP model, the sets of the constructive functions corresponding to them are compared. Table 1 represents a part of the functions connected with nodes, and table 2 – with edges of the POP model of the vapour-compressive refrigerating plant. These tables have the following structure: $m_i^1$ – a designation of the graph element of POP (nodes and/or arcs); $m_i^2$ – a designation of the elementary function; $m_i^3$ – verbal description of the elementary function for the given graph element; $m_i^4$ – an identifier of the elementary function; $m_i^5$ – the necessity of constructive implementation.
The search of descriptions of constructive elements for engineering solutions of RS is realised in the patent file and other sources of scientific engineering information. For all the elements, the sets of constructive functions performed by them are determined and the obtained result is described.

By results of this stage, the table of engineering solutions is filled in (table 3), where the attributes are the names of the elementary functions from tables 1 and 2. Each line of the table corresponds to one constructive element. The fields of the table contain the values of predicate function $P(f_i)$ which possesses a true or false value depending on the performance of corresponding function $f_i$, specified in the head of the table, by this element.

In most cases, constructive elements perform various sets of functions. Engineering solutions of RS are obtained by means of combining the elements so that to obtain sets from them, which perform all specified functions. One of the variants of engineering solutions ($A_6$, $A_4$, $A_5$, $A_8$, $A_3$, $A_1$, $A_2$, $A_5$, $A_3$, $A_9$, $A_7$, $A_{11}$) is marked out with rare section lining in table 3.

The number of elements in the engineering solution of RS can be different, which differs this approach from a morphological one. In a particular case, when elements perform similar sets of functions, this table is degenerated into a morphological one.

| $m_1^1$ | $m_1^2$ | $m_1^3$ | $m_1^4$ | $m_1^5$ |
|---------|---------|---------|---------|---------|
| $v_1$, HO | $f_3(e_1^{\text{then}})$ | Enabling refrigerating medium condensation | 001 | 1 |
Table 2. The list of the functions connected with the edges of the POP model

| $m_1^1$ | $m_1^2$ | $m_1^3$ | $m_1^4$ | $m_1^5$ |
|----------|----------|----------|----------|----------|
| $e_1^{\text{phas}}$ | $f_3(e_1^{\text{phas}})$ | Enabling refrigerating medium condensation | 016 | 0 |
| $e_1^{\text{ther}}$ | $f_3(e_1^{\text{ther}})$ | Enabling the heat feed in the condenser | 017 | 0 |
| $e_1^{\text{mech}}$ | $f_3(e_1^{\text{mech}})$ | Enabling refrigerating medium expansion | 018 | 0 |
| $e_2^{\text{ther}}$ | $f_3(e_2^{\text{ther}})$ | Enabling the temperature reduction of the refrigerating medium | 019 | 0 |
| $e_2^{\text{phas}}$ | $f_3(e_2^{\text{phas}})$ | Enabling refrigerating medium evaporation | 020 | 0 |
| $e_3^{\text{ther}}$ | $f_3(e_3^{\text{ther}})$ | Enabling the heat feed in the evaporator | 021 | 0 |
| $e_4^{\text{ther}}$ | $f_3(e_4^{\text{ther}})$ | Enabling the heat feed in the steam dome | 022 | 0 |
| $i_1$ | $f_3(i_1)$ | Enabling the refrigerating medium feed from the condenser to the flow control valve | 031 | 0 |
| $i_2$ | $f_3(i_2)$ | Enabling the refrigerating medium feed from the flow control valve to the evaporator | 032 | 0 |
| $i_3$ | $f_3(i_3)$ | Enabling the refrigerating medium feed from the evaporator to the steam dome | 033 | 0 |
| $i_4$ | $f_3(i_4)$ | Enabling the refrigerating medium feed from the steam dome to the radial compressor | 034 | 0 |

Table 3. The table of engineering solutions

| Alternative | A series number of the constructive function |
|-------------|-------------------------------------------|
| $A_1$       | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 |
| $A_2$       |                                           |
| $A_3$       |                                           |
5. Conclusions
The suggested method can be used in case the constructive elements perform different sets of functions and in case the development of morphological tables is hindered or impossible. This is conditioned by the fact that the model of the physical operating principle allows forming a table (table 3), where engineering solutions of the converters are obtained by means of joining functionally compatible elements.

The process of development of the model of the physical operating principle, determination of the multitude of constructive functions and compilation of the table of engineering solutions is implemented according to tough rules and almost does not depend on human intuition and, therefore, it is within the competence of a semiskilled engineer.

The study of the method does not require mastery of new concepts, and its application – utilizing specialised databases. The descriptions of engineering solutions taken from the patent file and other scientific and technical literature can be used as elements.

The method can be applied as a means of enhancing the labour efficiency of designers at early stages of designing owing to reduction of labour expenditures when choosing the concept of an engineering system for energy transformation, and also as a methodical support for development of computer-aided design systems.

6. References
[1] Alexeev G N 1980 General heating engineering p 552
[2] Koller R 1976 Konstruktionsmethode für den Maschinen, – Gerate – und Apparateban. (Berlin, Heidelberg, New York) p 430
[3] Fomenkov S A Davidov D A Kamaev V A 2004 Modelling and Automated Deployment of Structured Physical Knowledge p 278
[4] Veinik A I 1991 Thermodynamics of Real Processes p 576
[5] Veinik A I 1968 *Thermodynamics* p 464

[6] Kamaev V A Yakovlev A A 2006 Information Modelling of the physical operating principle and formation of a multitude of engineering solutions of energy converters *Information Technology* 1 2-8

[7] Shewchuk V P Yakovlev A A 2006 The Method of conceptual engineering solutions of energy converters *Industrial Power engineering* 3 41-46

[8] Baranenko A V Bucharin N N Pekarev V I Skakun V I Timofeevskii L S 1997 *Cooling Machines*

[9] Kurylyov Ye S Onosovskii V V Rumyantsev Yu D 2000 *Refrigerating Plants*

[10] Dyachek P I 2007 *Refrigerating machines and plants* p 424