SOCIO-ECONOMIC ASPECTS OF ENERGY EFFICIENCY CONTROL SYSTEMS FOR REFRIGERATING INSTALLATION

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1. Introduction

Energy efficiency as well as coefficient of performance (c.o.p.) of the refrigerating equipment is constantly being enhanced, but much remains to be done in this field. Compression is the most widely used refrigeration technology and electrical energy in it is the most commonly used source of energy [1, p.156-210; 2, p.134-141; 3, p.188-191]. The efficiency of a refrigeration plant is measured by using the c.o.p. The c.o.p. describes the relationship between the refrigeration effect provided by the plant and the energy consumed by the compressor; both types of energy are being expressed in the same units. The improvement of the energy efficiency of refrigeration plants is both socially and economically important process, since it reduces the main contribution of the refrigeration sector to the global warming through the energy consumption lowering. Issues are indirect emissions of CO2 induced by the consumption of energy needed to operate refrigeration plants.

To manage operation and decision making problems we have to know how the given refrigeration plant works on the end-user site in real life from the energy consumption point of view. The experience on sites could give us cost data related to real energy consumption per refrigeration output. It might be considerably different from the refrigeration design. In many cases the losses of electrical energy could be found only after an execution of some complex measurements. Almost all existing control systems could not apply continuous measurements to find a flaw, then to provide technical diagnostics and to improve current situation. We have to measure a value of this parameter, before to say something about energy efficiency. The key issue here is to know the specific power consumption, for what we need to measure refrigeration output, which, in its turn, leads to measurements of refrigeration mass flow rate.

There are many methods to measure the above values, but most of them can be used only for special tests of refrigeration equipment or systems at the factories and are not practically available at customer sites [4, p.26-32; 5, p.230-267]. In other words, the technically practical and economically acceptable, and not yet commonly known way for continuous measurement of specific energy consumption should be suggested.

2. Task setting and solution

The set of requirements to the approach should be as follows:

- refrigerator energy efficiency monitoring should be done continuously;
- determination of energy efficiency, quantity of produced artificial cold and consumed energy should be done for any chosen by end-user time interval;
- low cost.

The application of such method could be saving money due to competent management of the given refrigerator.

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The purpose of this paper is to examine how to use motor-compressor characteristics together with necessary measured data in a refrigeration unit for indirect determination of refrigerant mass flow in small and medium capacity systems.

Proposed monitoring system should be constructed in the way where continuously occurs:

- measurement of electrical power that feeds the refrigeration unit, and, as a result, subsequent calculation of consumed electric energy amount;
- measurement of refrigerant temperatures and pressures at necessary points of the reverse cycle and calculation the appropriate specific enthalpy values;
- indirect determination of refrigerant mass flow and subsequent calculation of produced artificial cold amount.

Determination of energy efficiency for the given refrigeration unit as the ratio of produced cold to the electrical energy consumed, a comparison of this value (as option) should be done with: designed, theoretical, idealized for the Carnot cycle, manufacturer data (which the manufacturer claimed for the given unit), or technically acceptable for considering installation.

Results of the above comparison should be formalized in understandable terms for end-user (e.g., in color: «green» - energy efficiency is within the acceptable thresholds, «yellow» - energy efficiency is below the norm, «red» - energy efficiency is much lower than the norm). In the case of reducing energy efficiency, the analysis should be done to evaluate technical condition and operation level of refrigeration unit with the aim to make a decision on their further use (repair, replacement, etc.).

Accumulation and prolonged storage of necessary measured and calculated parameters, trends identifying future behavior of considered unit (improvement, deterioration or stable value of energy parameters) and their indications also should be provided.

A distinctive feature of proposed method is the way of indirect refrigerant mass flow determination. Content of the method is as follows: we should measure the current values on electrical motor terminals, namely – voltage, current and active power. Further knowing from manufacturer the nominal motor parameters we could calculate the mechanical power on the motor shaft. Simultaneously the pressures and temperatures at correspondent certain points (see below) should be measured, than for those points the correspondent enthalpy values should be calculated. The next two steps are to find the specific refrigeration capacity and the specific compression work. Power on the motor shaft comprises of permanent mechanical losses and compression work. To determine the latter we could multiply previously calculated power at the shaft by the special coefficient - α. It is well known that α is placed within the range 0.85…0.95. Next step is to determine the refrigerant mass flow assuming that the considered plant is under quasi-stationary conditions.

Figure 1 depicts the algorithm that is used to show what parameters (values) should be measured and calculated to find the specific power consumption (ε).

The amount of heat removed (Q_{12}) and energy supplied (W_{12}) could be found when integrating instantaneous values of refrigerating capacity and true electrical power input within a certain chosen time interval t_1, t_2.

The last step is to find ratio $\varepsilon = Q_{12} / W_{12}$, which is based upon measured parameters and reflects the "quality" of supplied energy use.

The more detailed mechanical power definition on the electrical motor shaft (or, the same, on the direct drive compressor) is shown below. Basic information needed is the motor manufacturer data which present nominal values of parameters, next are values measured directly on electrical motor terminals, also the phase-substitution circuit will be used.

Power consumption in nominal regime

$$P_{el\ ter\ nom} = \frac{P_{shaft\ nom}}{\eta_{nom}} \quad . \tag{1}$$

Stator nominal current

$$I_{el\ ter\ nom} = \frac{P_{shaft\ nom}}{3 \cdot U_{el\ ter\ nom} \cdot \cos\varphi_{nom} \cdot \eta_{nom}} \quad . \tag{2}$$

Total losses

$$\Delta P_{\Sigma\ curr} = \Delta P_{copper\ s\ curr} + \Delta P_{copper\ r\ curr} + \Delta P_{iron\ curr} + \Delta P_{add\ curr} \quad . \tag{3}$$

Then the current mechanical power at the motor shaft (at the compressor shaft)

$$P_{shaft\ curr} = P_{el\ ter\ curr} - \Delta P_{\Sigma\ curr} \quad . \tag{4}$$

Above the formulas for three-phase asynchronous motor has been used, but the similar calculation could be made for any other electrical machines used in refrigeration engineering.

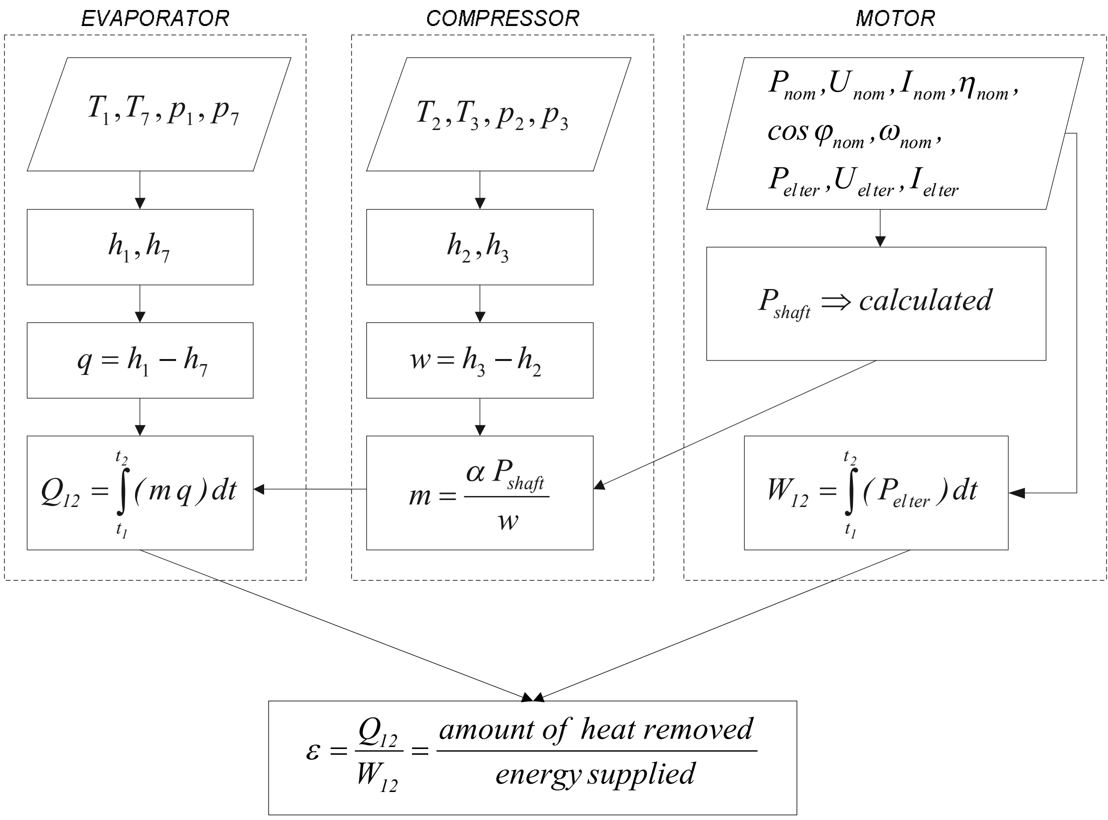

Fig. 1. Algorithm for determination of the specific power consumption

On the basis of carried out analysis for existing methods to control, estimations of power efficiency and mathematical models for small productivity refrigerating compressor installations (RCI) research tasks are validated. It is shown, that the effective decision of RCI control problems is impossible without mathematical modeling of dynamic and static modes of their work. From positions of automatic control theory, the analysis of basic properties of household refrigerating devices (HRD) and air micro compressors (AMC) devices for artificial ventilation of lungs is carried out. Mathematical models (MM) of HRD and AMC with use of fundamental laws of refrigerating engineering and hydro gas dynamics are suggested.

Mathematical models are created and problems of identification of parameters for some modern electric executive mechanisms of compressors (EEM) are solved: an asynchronous, brushless direct current, switched reluctance motor (SRM). Sharing of created MM for HRD, AMC with developed MM of EEM have allowed to synthesis highly effective different function control systems for HRD and AMC. The created MM has allowed using already on design stage of control system an estimation of their power properties resultants.

The single-channel control system for HRD evaporating temperature is developed. The new system has allowed to essentially lower the energy consumption, to raise power factor (up to 0,98), to lower (from 3 to 7 %) mass and dimensions parameters of HRD hermetic compressors, to ensure their functioning under essentially lowered voltage supplied, to reduce starting currents and to provide astatic temperature control for HRD refrigerating chambers. The two-channel control system for HRD is developed. This new system has allowed, at the expense of simultaneous extreme control on minimum energy consumption for evaporating and condensing temperatures to lower energy consumption, in comparison to known “hysteresis” system, up to one and a half times.

The fuzzy control systems for AMC are developed. The difference from known fuzzy regulators is in application of the formalized rules for fuzzy conclusion, also the shift of accessory functions and robust realization of PID-ALGORITHMS for control systems. Created system for AMC has shown high efficiency of control processes for pressure/flow of air-gas mixes in lung artificial ventilation devices.

Mathematical model and block diagram of control system for HRD providing realization of partially-invariant control laws to static loading from the hermetic compressor have been developed. It is shown, that application of suggested control system allows to lower speed pulsations (up to 9 %), to expand the range of productivity control (not less than to 3 times) and to lower mass and dimensions parameters of hermetic compressors. All developed MM are verified by means of automatic control systems experimental samples and the measuring equipment.

MM are created and highly effective, providing extreme control (minimum of network current, also COP maximum) system is suggested for asynchronous EEM in hermetic compressors, both for usual manufactured type also developed for the first time. Methods of MM for switched reluctance motor (SRM) in EEM compressors have developed. Methods of calculation are suggested and experimental samples of control system with switched reluctance motor (SRM) are created. The mathematical model and the experimental stand for SRM identification parameters are created. On the basis of developed detailed EEM for SRM and some experiments, the Kostenko control laws were expanded on the control systems with SMR EEM. The change in a design of asynchronous three-phase electric motors for the hermetic compressors has been suggested, which provides decrease of mass and dimensions parameters of hermetic compressors for not less than 7 % when supplying energy from controlled inverter with increased frequency.

Algorithms of power factor proof-readers in compressors control systems are improved. The design of combined position gauge and SRM rotor speed is suggested. On the basis of SCADA environment and DSP processor, the multichannel information measuring system is created. Small-sized piezoelectric gauges of pressure and flow of gas and liquid mediums are developed. All these listed designs have passed experimental tests.

New methods of identification of electric refrigerating factor and parameters for basic elements of control systems are suggested. The experimental stand is developed and studies of HRD are carried out in its productivity control mode which confirmed high efficiency of created control system. The suggested control systems are introduced on machine-building enterprises of Ukraine.

3. Conclusions

Low cost of the proposed system could give a possibility to install it on all new domestic refrigerators and relatively large capacity commercial systems to inform end-users. Implementation of this method of monitoring energy efficiency will allow most efficient use of energy resources through the timely conduct of steps necessary to control operations to repair and maintenance.

Further development in the area could become as a system for troubleshooting and diagnostics, often called also as FDD - fault detection and diagnostics, which should be able to locate the place, e.g. machine, device or group of devices in refrigeration plant, where improper operation significantly reduces efficiency of the entire refrigeration system.

Nomenclature

α – coefficient, (-)
η – efficiency, (-)
ω – angular velocity, (s-1)
ε – specific power consumption, (kJ/kW·h)
h – enthalpy, (kJ/kg)
h – height of motor axis, (mm)
I – current, (A)
M – torque, (N·m)
m – mass flow rate, (kg/s)
p – pressure, (Pa)
P – true power, (W)
Q – amount of heat, (kJ)
q – specific enthalpy, (kJ/kg)
T – temperature, (K)
U – voltage, (V)
W – energy, (kJ, kW·h)
w – work, (J)

Subscripts

1 – beginning of time interval, evaporator outlet
2 – end of time interval
7 – evaporator inlet
el ter – electrical terminals
shaft – at the shaft
nom – nominal
mech – mechanical losses
add – additional
curr – current value
r – rotor
s – stator
copper – belongs to electrical losses in windings
iron – belongs to magnetic losses in iron

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Summary

The proposed systems could be included in domestic or low-powered commercial refrigerators for continuous monitoring of energy efficiency, or, in other words, to check the “quality” of electrical energy consumption, which in turn presents their technical conditions and levels of management and operation.

Keywords: control; household refrigerating device; air micro compressor; identification; electrical executive mechanism; mathematical model; hermetic compressor; energy efficiency.

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