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Energy Flow Modelling Method of Energy Efficiency Improvement for Power-Using Electromechanical Products

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Abstract: As a crucial factor in the improvement of energy efficiency for power-using electromechanical products, the flow, conversion and distribution of energy are closely related to design variables of products. Simultaneously, performance is the constraint of energy efficiency and is strongly affected by design variables. In order to improve a product's energy efficiency without compromising performance, an energy flow model with a basic energy flow element (EFE) was built on a functional basis and its modelling procedure is presented in this paper. Containing function, design variable and characteristic energy in EFEs, as well as the interface parameters between EFEs and environment, the model contributes to logically clarifying the relationship between design variables and performance. With the refrigerator as an example, the effectiveness of the energy flow model is verified by a comparison between simulation, based on an energy flow model, and experimentation. Furthermore, five critical design variables of a 265 L refrigerator were screened with the model. Test results of the improved prototype meet the requirements of operating rate and temperature uniformity, and the daily electricity consumption was reduced by about 9%. Comparison between the design results of the energy flow model and the testing results of the prototype demonstrates that the energy efficiency improvement method based on energy flow model is effective.

Keywords: energy flow model; characteristic energy; performance design; energy efficiency improving

1. Introduction

The rapid depletion of primary energy sources and the urgent need to reduce carbon emissions have led to grim energy-saving circumstances. Worse still, global energy demand is supposed to grow by 0.3~0.95% every year by 2050 in many energy outlooks published by the IEA [1], IRENA [2], OPEC [3] and BP [4], though in a context in which global economic and energy development have been terribly hit by COVID-19. Energy-using electromechanical products is the main source of energy consumption, and energy efficiency improvement for these products would have a significant social benefit and be an effective way to improve energy conservation and carbon reduction for manufacturing enterprises [5]. Meanwhile, performance guarantees are the constraints and premises of product energy efficiency, while energy saving and consumption reduction pose new challenges to the performance design of energy-consuming electromechanical products.

Several energy-saving unit technologies, such as the optimized design of component structure [6,7], reduced design [8] and machining processes [9], and intelligent control technology [10] have been developed to improve energy efficiency within the limited scope of the product design process. However, conflicts may potentially emerge between energy consumption and performance at the detailed design stage when the energy-saving unit technologies outlined above are applied in the design of energy efficiency. For instance, an increase in fan air volume in the air circulation system of an air-cooled refrigerator can improve cooling rate but may increase energy consumption. The match of the fan

air volume and the cabinet parameters is essential to balance cooling rate and energy consumption. Therefore, when it comes to electromechanical products with complicated structure and function, the conflicts need to be solved via performance design from the perspective of product or system. In other words, the key to solve the performance matching problem after the addition of energy saving and consumption reduction targets is to analyze the correlation between multiple design variables and performance and energy consumption.

Energy plays a crucial role in consumption reduction and energy saving and is also an important guarantee for the performance of electromechanical products [11]. Reasonable flow and distribution of energy during performance matching can reduce the waste of energy resource as much as possible on the basis of ensuring the achievement of product performance, and thus achieves an effective balance between energy efficiency improvement and performance assurance. Meanwhile, flow, conversion and distribution of energy rely on the design variables of components and parts. In addition, as a universal and fast method to energy efficiency optimization, performance matching for products or systems is indispensable under the trend of mass personalized production [12,13]. As a consequence, in consideration of the pivotal role on the product functions and performance that energy plays during the actual operating processes of energy-using electromechanical products, performance matching based on energy distribution should be researched. Furthermore, identifying how a set of design variables affects energy efficiency and performance through the use of energy is foundation and key.

In terms of performance matching, several studies have attempted to balance product performance and energy efficiency [14,15]. In these studies, there is a lack of description of the interactive relationship between multiple design variables and multiple performances, so it is hard to give intuitive expression to the interactive relationship among design variables, energy and performances.

As for energy, with its essential effect on the implementation of functions and on performance via the use of power [16], it also plays a significant role in functional expression throughout the conceptual design phase. Work on energy flow started more than 30 years ago. The concept of flow was addressed by Phal and Beitz, based on which anticipative functions were performed by energy, material, and signal flow among components [17]. Building upon this study, the implementation of functions relies on the conversion and transfer of the three flows above. Energy flow among these plays a decisive role with energy borne by material flow and controlled by signal flow. In order to adopt a standardized design language, Stone proposed a mode of functional expression called functional basis, which consists of "verb + noun" [18,19]. Such a concept, in which the "verb" denotes the action acting on the energy and the "noun" denotes the various forms of energy, is conducive to simplifying the functional structure of product. Additionally, besides the important role on function implementation, the action form and law of energy is also strongly associated with performance implementation. The "substance-field" theory from TRIZ reveals the rules that dictate how performance implementation rests with the interaction between parts and energy [20].

In addition, energy has been studied by system modelling. H. M. Paynter proposed a bond graph method that includes interactions among different physical domains to describe various parts of composition, conversion, logic relationship and physical characteristics based on energy and energy exchange for complex mechatronics systems [21]. Modelica is an object-oriented, declarative, multi-domain modeling language for the modeling of physical systems containing mechanical, electrical, electronic, hydraulic or thermal subcomponents [22,23]. The Modelica Standard Library contains over 1600 model components and 1300 functions in many fields [24]. Considering that the three-dimensional structural model is usually turned into a topological structure in the Modelica modeling method, characteristic parameters rather than structure parameters are used so that Modelica is unable to express how design variables affect the performance of each energy flow process. Therefore, this model can only be applied to verify the feasibility of products and complete

the simulation of an entity model or system, due to the small amount of quantitative guidance for performance optimization logically.

The energy modelling methods above have been used in concept design stages in many fields such as automobiles [25,26], engineering machinery [27,28], the international space station [29] and biological engineering technology [30]. However, they cannot be applied to the detailed design stage since none of them built a relationship among design variables, energy flow and performance quantitatively or accurately.

During the detailed design stage, some scholars have combined design variables and energy to analyze the influence of energy flow on performance for complex electromechanical products quantitatively. Gao et al. proposed an energy loss model that considered the oil leaks and friction associated with clearances in the slide guide system of a hydraulic press to find the optimum fit clearances with a decreased pillar weight, something which is conducive to the improvement of energy efficiency for a single aspect instead of a whole product or system [31]. Wang addressed energy flow element (EFE), consisting of structural element (D), interface (T) and energy variation (ΔE), as the basic object of energy flow analysis [32], and has achieved good results in the area of vehicle passive safety [16,33]. Duan optimized the cold dissipation and temperature uniformity of a refrigerator based on energy flow element [34]. However, the studies above were carried out under a single performance constraint in passive energy absorption and dissipation conditions while in an active energy consumption condition, therefore, it is difficult to analyze the comprehensive effect of design variables on multiple energy functions and performance objectives.

To sum up, energy analysis is one of the most efficient ways to explore performance matching under the constraint of energy efficiency. Although an amount of effort has been made to discuss energy expression model for complex energy-using electromechanical products, the relationship and quantitative characterization among design variables, energy and performance are still inadequate. A large number of engineering tests have to be designed to model the relationship between design variables and product performance when designing new products [35,36]. In order to ascertain how design variables impact the response of energy efficiency and performance to instantly support performance matching, energy flow element was redefined and an energy flow model based on functional basis was built. The model was built using characteristic energy as a bridge to analyze the influence of design variables on multiple performances for complex energy-using electromechanical products.

2. Energy Flow Model

Product performance, a premise and constraint for power-saving and consumption-reducing design, is an evaluation measure for design solutions under the combined effects of function, structure and environment. The energy efficiency of a product has to do with how efficiently it uses power in the process of accomplishing function and performance by transferring and distributing energy between and within parts of the product. According to functional basis theory, complex products are composed of functional modules that possess diverse structures and perform different functions. Generally, the structure sustains energy action, and the energy is what allows the structure to fulfill its function. As a result of energy conversion within functional structures and energy transfer between different functional structures, the product's function is realized and expressed through energy efficiency and performance. Therefore, energy flow is the critical factor accounting for product performance and energy efficiency. For the sake of performance matching with energy efficiency improvement, an energy flow model based on functional basis needs to be established to intuitively describe the relationship of influence between energy, structure and performance.

In this section, "energy flow element" is defined, firstly, as the basic unit for describing the conversion and transfer of energy for energy-using electromechanical products. After that, environment and transmission of energy in energy flow model are illustrated. Finally,

the energy characteristic equation is developed to calculate characteristic energy, which can be used to analyze energy action characteristics.

2.1. Defining Energy Flow Element Based on Functional Basis

During the conceptual design stage, functional basis is standard vocabulary used when decomposing the global function of a product into smaller sub-functions. It is a set of functions and flows with specific definitions, expressed in the form (verb + noun) for each sub-function (Figure 1). Energy flow and conversion of functional basis are the key point and elementary unit of power consumption, respectively. In our study, the concept of functional basis is extended to consider the quantization characteristics of the basic units undergoing energy conversion or transfer, and the effects that such characteristics have on performance. Therefore, "energy flow element" is defined as a basic unit based on functional basis. Energy flow element is composed of one or more parts with strong structural correlation and energy interaction and can achieve a certain function through energy conversion or transfer independently (Figure 2).
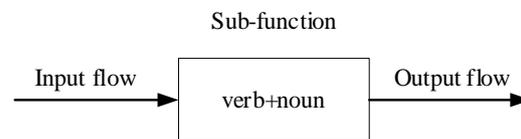
Figure 1. The expression of a functional basis for a subfunction.
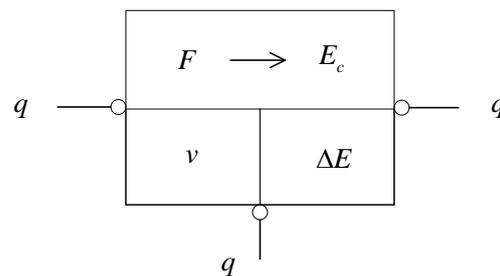
Figure 2. EFE model.

The information such as function, design variables, energy variation and interfaces in energy flow element are as follows:

- Function (F). F represents the function (energy conversion or energy transfer) realized by the EFE and determines the type and internal connection of input and output energy in the course of energy conversion or transfer. For example, the function of an electric motor is to convert electrical energy into mechanical energy while the function of a heat exchanger is to transfer the heat energy from internal fluid to external fluid.
- Characteristic Energy (E_c). E_c represents the energy value to realize the function of the EFE and also the index to evaluate performance realization. It will be elaborated in the following sections.
- Design Variable (v). v represents a set of design variables containing physical characteristic parameters and geometrical structure parameters, giving a quantitative description about characteristics of energy conversion and transfer and determining the quantitative relation between input and output energy.
- Energy Variation (ΔE). ΔE represents the difference between input energy and output energy during the course of function implementation, including energy dissipation and energy storage or release with EFE's state changing.
- Interface (q). q represents the interface when transferring energy between EFEs, including interface geometric states and parameters, interface state parameters related to energy flow and control signals. Interfaces have also been adopted in other mod-

eling approaches. For example, they are referred to as "port" in bond graphs and "connector" in Modelica.

Based on the definition above, an EFE model can be further elaborated in view of concrete forms of energy action. Typically, there are three types of EFE models, including converting input energy to another output energy (such as compressor), converting input energy to energy change of the EFE itself (such as chassis frame) and transferring the same type of energy from one place to another place (such as condenser).

In order to better elucidate the EFE model, the compressor, one of the three types of EFE models, is taken as an example. Firstly, from a functional basis point of view, a compressor can be represented as shown in Figure 3 in the conceptual design stage. Its function is to convert electrical energy into heat energy of refrigerant. Obviously, according to functional basis, what determines its function is the conversion and transfer of energy, that is, the content described in the "verb" part. However, what makes a critical difference to performance response in EFE model is a compressor's quantitative characteristics. As a result, the actual physical form of a compressor, such as theoretical volumetric capacity V_{th}, volume efficiency η_v and isentropic efficiency η_i, needs to be defined to establish the EFE model of the compressor, which contributes to the transition from functional design during conceptual design stage to detailed design (Figure 4).
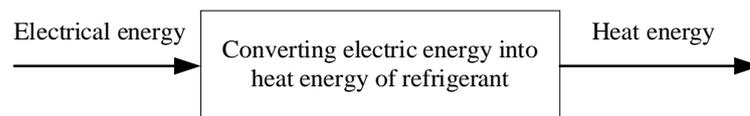
Figure 3. Functional basis model of compressor.
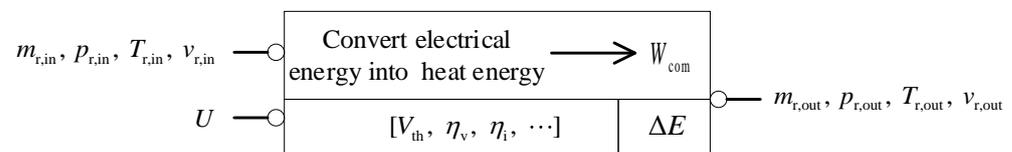
Figure 4. EFE model of compressor.

In the EFE model of compressor, the input parameters U (alternating current voltage), $m_{r,in}$ (input flow quantity of refrigerant), $p_{r,in}$ (input pressure of refrigerant), $v_{r,in}$ (input flow velocity of refrigerant) and $T_{r,in}$ (temperature of refrigerant) on the left side are status parameters of electrical energy, while the output parameters $m_{r,out}$ (output flow quantity of refrigerant), $p_{r,out}$ (output pressure of refrigerant), $v_{r,out}$ (output flow velocity of refrigerant) and $T_{r,out}$ (output temperature of refrigerant) on the right side are status parameters of heat energy. In the upper box, a description of compressor function is provided, and W_{com} represents the amount of energy conversion to realize the function. In the lower box, V_{th}, η_v and η_i are design variables, and ΔE is the energy variation between input and output. Obviously, compared to functional basis, an EFE model with design variables and energy value contributes to the quantitative characterization of the relationship among design variables, energy and performance.

2.2. Energy Transmission

For energy-using electromechanical products, energy conversion in each EFE and energy transmission through the interface between different EFEs arrive at the accomplishment of a function and influence the energy efficiency. Energy transmission from an EFE to another, consisting of energy type, size and direction, describes the causality of energy between EFEs. As is demonstrated by Stone in their research on energy modeling in conceptual design, the function of a product determines the type of energy to be conveyed, and the direction and magnitude of these transfers are critical factors in determining product performance [19].

In an energy flow model, energy transmission is represented by directed line segment between EFEs. Two ends of the line segment are connected to EFE interfaces, indicating that the characteristics of energy transmission depend on the corresponding state parameters of the interfaces. The direction of the line segment represents the direction of energy flow and the causal relationship of energy transmission from source EFE to target EFE, namely that energy from source EFE is equal to energy into target EFE. For example, as shown in Figure 5, energy is transmitted as the refrigerant flows from compressor to condenser through a pipeline in the refrigerator, so that flow rate, pressure and temperature of the refrigerant at the compressor output are the same as those at the condenser input.
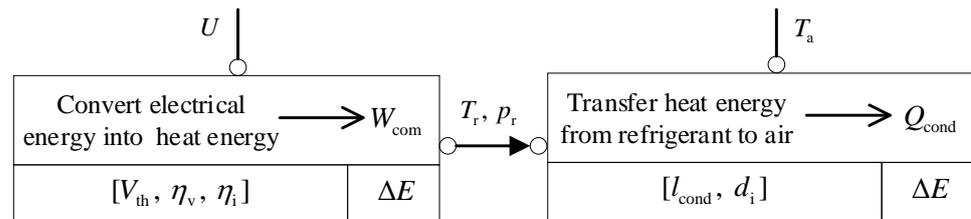
Figure 5. Energy transmission between compressor and condenser.

The quantitative characteristic of energy transmission is strongly associated with interface state parameters. Based on bond graph theory this can be expressed as:

$$P(t) = \int_0^t e(t) \times f(t)dt, \tag{1}$$

where $e(t)$ is generalized potential variable and $f(t)$ is generalized flow variable. $P(t) = e(t) \times f(t)$ has dimension of power, so the quantitative characteristics of energy can be described more concisely when a system reaches a steady state. As seen in Equation (1), generalized potential variable and generalized flow variable, which can be obtained with the interface state parameters of EFE, are key to obtaining energy transmission. The relationship between the interface parameter and a generalized variable is illustrated in Figure 6.
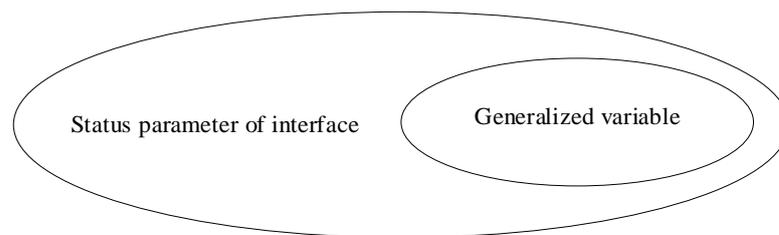
Figure 6. Relationship between the interface parameter and a generalized variable.

For example, as for the condenser in Figure 5, the heat exchange process for the internal refrigerant is a constant pressure heat exchange process. In the process, the specific enthalpy h_r (J/kg) of the refrigerant is the generalized potential variable and the flow quantity m_r (kg/s) is the generalized flow variable, so the product $P = m_r h_r$ (W) can be used to measure the energy transferred between input and output refrigerant at steady state. In other words, the energy reduction of the refrigerant flowing through the condenser EFE at steady state equals the energy difference between input and output energy, $m_r (h_{r,in} - h_{r,out})$. In the condenser EFE, the potential variable h_r can be derived from the state equation by using the interface state parameters (T_r, p_r). Therefore, energy transferred between EFEs can be calculated by using the interface state parameters.

2.3. Environment

As is shown in Figure 7, the boundary in an energy flow model is defined as the environment when energy is converting and transferring in a product or system.
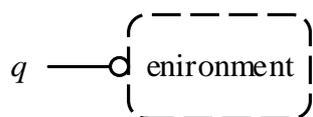
Figure 7. EFE model of environment.

In order to make the expression of environment consistent with the energy flow element in an energy flow model, a similar method is used to describe the characteristics of environment.

- Function. The function of environment is to provide a source of energy for the product or system, or to receive energy generated by the product or system.
- Design Variable. The environment is immutable and has an effect on the product or system as objective boundary condition when designing, so there is no design variable.
- Energy Variation. The environment with a physical scope far greater than the product or system is objective and for which there is an infinite capacity for energy supply or energy absorption, that is, the energy variation is arbitrary in terms of energy absorbed or released.
- Interface. Energy transfer between environment and other EFE is carried out through the interface. Since the environmental state does not change, the interface state parameters of the environment remain unchanged and only serve as the boundary of energy action in the product or system.

For example, a power grid with constant and stable voltage can be regarded as the environment of a household appliance, since it can provide power for multiple appliances at the same time. In addition, it should be noted that the determination of the environment has to do with the energy effect of the product or system. In the case of indoor air, the energy effect will significantly influence the air temperature so that the indoor air should be treated as EFE as for conditioner; however, for a household refrigerator, the effect of heat on temperature is negligible, so indoor air should be treated as the environment.

2.4. Energy Characteristic Equation

In order to study the relationship between EFE energy action and performance realization via energy flow model, it is indispensable to establish an energy index to evaluate EFE performance. Based on the energy conservation law, characteristic energy was defined as an index to evaluate EFE performance, and the energy characteristic equation was established to calculate the characteristic energy.

The amount of energy involved in EFE should remain constant according to the energy conservation law. That is, the total energy of EFE input is equal to that of EFE output plus the energy loss, as is shown in Equation (2).

$$\sum_{k=1}^{n} E_{k,in} - \sum_{k=1}^{m} E_{k,out} = \Delta E, \tag{2}$$

where $\sum_{k=1}^{n} E_{k,in}$ and $\sum_{k=1}^{m} E_{k,out}$ are the energy of input and output respectively. ΔE represents energy loss.

Equation (2) elucidates the macroscopic regularity of energy conservation in EFE with the form, magnitude and path of energy. However, it is difficult to clarify the influence of design variables and interface parameters on energy conversion and transfer without an index containing design variables and interface parameters. In addition, according to functional basis theory, what determines energy efficiency and performance is the transformation or transfer of energy, that is, the content described in the "verb" section. Therefore, the quantitative nature of the energy conversion or transfer effect in the EFE model is the key and bridge to the degree of performance realization. In order to establish the relationship between design variables and function/performance, from the point of energy, characteristic energy is defined as a bridge to indicate the relationship between energy and performance. To illustrate the characteristic energy of EFE in a general sense,

it is necessary to analyze the quantitative characteristics of EFE in its function realizing process through energy, and energy characteristic equation is introduced to calculate and characterize the characteristic energy in this paper. The characteristic energy is defined as follows:

Definition 1. *Characteristic energy (E_c) refers to the energy of the transformation or transfer required to achieve the function in EFE.*

In the example of compressor, the main purpose of a refrigerator compressor is to convert electrical energy into refrigerant heat energy. Hence the characteristic energy is the compression energy expressed as Equation (3):

$$W_{\text{com}} = m_{\text{r}} p_{\text{r,in}} v_{\text{r,in}} \frac{\kappa}{\kappa - 1} [(\frac{p_{\text{r,out}}}{p_{\text{r,in}}})^{\frac{\kappa-1}{\kappa}} - 1] / \eta_{\text{i}}, \tag{3}$$

As the characteristic energy emphasizes the energy response of design variables and interface parameters in the fulfillment of the function/performance, the energy characteristic equation of the characteristic energy may also be written as Equations (4)–(7) associated with the design variables to generate optimization of design data:
Power consumption of the compressor

$$W_{\text{com}} = \frac{m_{\text{r}}(h_2 - h_1)}{\eta_{\text{i}}}, \tag{4}$$

Outlet specific enthalpy

$$h_2 = h_1 + \frac{W_{\text{com}} - Q_{\text{k}}}{m_{\text{r}}}, \tag{5}$$

Refrigeration flow

$$m_{\text{r}} = \frac{\eta_{\text{v}} V_{\text{th}} N}{v_{\text{r,in}}}, \tag{6}$$

Thermal dissipation externally

$$Q_{\text{k}} = U A_{\text{k}} (T_{\text{r,out}} - T_{\text{a}}), \tag{7}$$

where h_2 and h_1 are the enthalpies at the compressor inlet and outlet respectively; Q_{k} is the thermal dissipation externally; UA_{k} is the compressor's overall thermal conductivity; T_a is the ambient temperature. In other words,

$$W_{\text{com}} = m_{\text{r}} p_{\text{r,in}} v_{\text{r,in}} \frac{\kappa}{\kappa - 1} [(\frac{p_{\text{r,out}}}{p_{\text{r,in}}})^{\frac{\kappa-1}{\kappa}} - 1] / \eta_{\text{i}} = \frac{(h_2 - h_1)\eta_{\text{v}} V_{\text{th}} N}{v_{\text{r,in}}} + U A_{\text{k}} (T_{\text{r,out}} - T_{\text{a}}). \tag{8}$$

Equation (8) describes the relationship between energy action of EFE and input as well as output energy. The middle formula of the equation reflects the quantitative properties of realizing function, namely the identification compressor EFE performance, while the right formula of the equation reflects the change of the input and output energy. Obviously, the preceding values are associated with design variables and interface parameters. According to the calculation idea of the characteristic energy of the compressor, the energy characteristic equation for calculating characteristic energy can be derived as shown in Equation (9):

$$E_{\text{c}} = \sum (E_{\text{source,in}} - E_{\text{source,out}}) = \sum (E_{\text{target,out}} - E_{\text{target,in}}) + \Delta E, \tag{9}$$

where E_{source}, $E_{\text{target}} \in \{E_1, E_2, \cdots, E_n\}$, E_{source} and E_{target} represent source energy and target energy in energy conversion or transfer respectively. That is, the characteristic energy measures the transfer of energy from source energy to target energy.

For complex energy-using electromechanical products, characteristic energy can be calculated with energy characteristic equations directly through numerical calculation for physical characteristics of EFE, and can be also obtained by modelling and characterizing calculation with three-dimensional distribution characteristics using a finite element method or constructing a characteristic energy fitting law under different operation conditions with fitting test data.

In conclusion, an energy flow model based on EFE for a functional basis has been proposed by Stone. Taking function as a carrier and energy as a bridge, increasing elements such as design variables, interface, characteristic energy and variation of energy, it can help to express the behavior and characteristics of the components in energy action, and characterize identification of EFE performance.

2.5. Comparisons with Other Existing Energy Modeling Methods

In this paper, the energy flow expression was used to realize the transition from conceptual design to detailed design, and for analyzing the relationship between energy effect and energy efficiency. A comparison between this and other existing energy modeling methods is given in Table 1.

Table 1. Comparisons with other existing energy modeling methods.

	Factors	Function	Interface	Environment	Part and Design Variable	Metrics of Evaluating Performance
Energy modeling methods	Expression of input and output streams [17]	√	×	×	×	×
	Functional basis [19]	√	×	Boundary conditions	×	×
	Energy model [32]	×	Only expressing connection relationship and flow direction	×	√	Energy variation
	Energy flow model in the paper	√	Containing interface status parameters	√	√	Characteristic energy

√ means that the factor is contained in the method; × means that the factor is not contained in the method.

It can be seen that the method of expressing energy flow in this paper is based on the energy modeling method during conceptual design stage proposed by Pahl and Stone, and enriches the design variables, interfaces and environment characteristics of the energy flow element with functions. Based on the existing energy flow modeling and analysis methods, characteristic energy is used as the energy index for evaluating performance instead of energy variation, which is better applicable to general energy-consuming mechanical and electrical products.

3. Modelling Procedure

The energy flow model of energy-consuming electromechanical products illustrates the relationship between energy and design variables in the process of performance realization, allowing improvements in both energy efficiency and performance. Its establishment is the process by which the components of the function are described through the expression of energy flow, the environment, and the energy transferred between them. In order to establish energy flow model of electromechanical products under the constraints of energy efficiency and performance, the function is represented by EFEs and energy transferred among them.

Figure 8 illustrates the process of creating an energy flow model for electromechanical products. Pahl believed that function is the transformation or transfer of material flow, energy flow and signal flow, and proposed a step-by-step decomposition method for

it [17]. Stone proposed that product functions can be expressed using functional chains consisting of functional bases and energy transfer between functional bases. Using the above functional modeling approach, starting from the function-based modeling method in conceptual design, the concerned function and performance are performed with a series of energy conversions or transfer effects by establishing a functional chain under energy efficiency and performance constraints. On the basis of functional chain, the functional basis is divided into energy flow elements according to the series criterion, parallel criterion and the type of design problem, and then the characteristics of these elements are defined. Lastly, characteristic energy of the product or system that has energy flow elements is calculated.
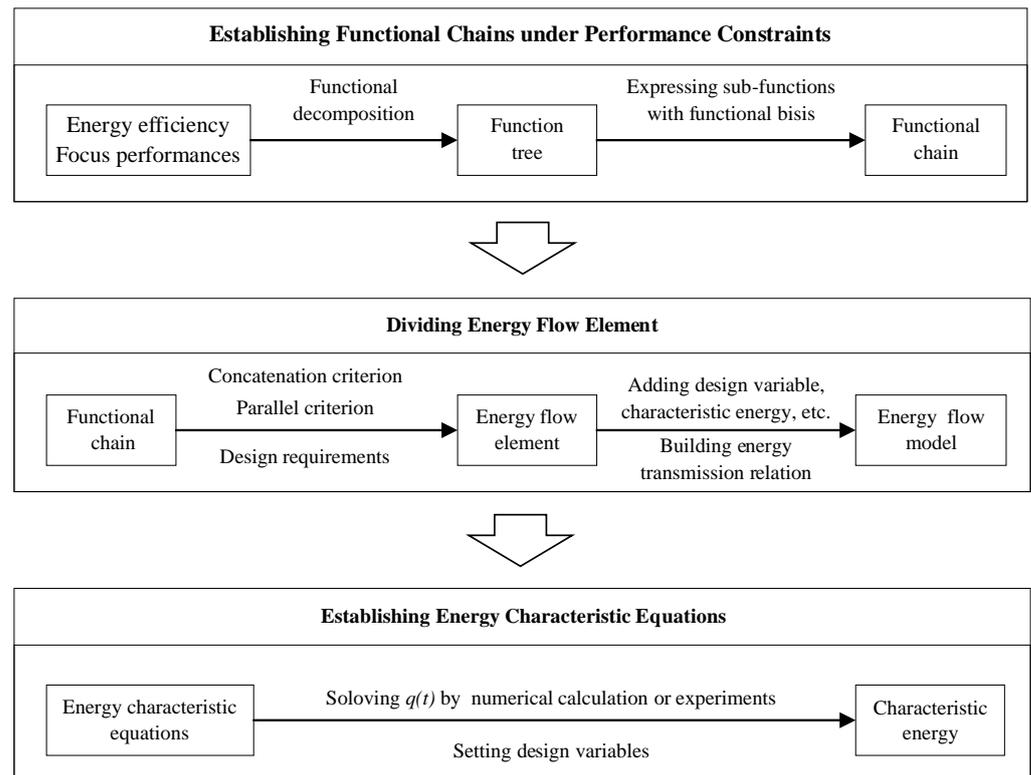
Figure 8. Energy flow modelling procedure.

3.1. Establishing Functional Chains under Energy Efficiency and Performance Constraints

Since the guarantee of performance is a prerequisite for improving energy efficiency and energy flow model is different according to which target performances are focused on, the first step of an energy flow model for energy efficiency improvement is to set up product functional chain under constraints of energy efficiency and performance. It should be noted that the function/performance of the energy flow model must be related to energy, that is, the performances unrelated to energy, such as appearance and surface characteristic, are not considered in this paper.

After determining the focused performances for electromechanical products, functional decomposition can be carried out based on Paul's method of function–structure analysis to form relevant function tree. During functional decomposition, a more detailed relationship between function and energy is supposed to be built step by step with the energy action in the process of realizing functions at all levels of the considered function tree, as is shown in Figure 9. Function F0 is decomposed into F1, F2 and F3 while F1 is decomposed into F1.1, F1.2 and F1.3, and each function is linked through energy flow.
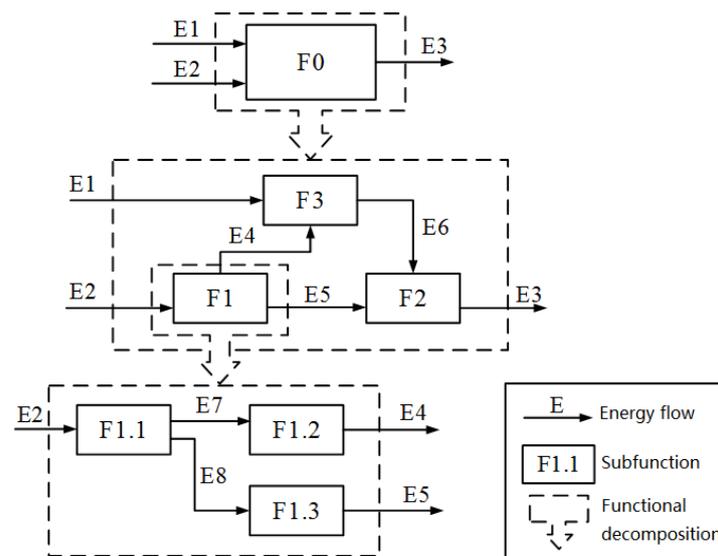
Figure 9. Functional decomposition based on function tree.

As is demonstrated in Figure 9, the focused function/performance is decomposed step by step to the terminal function (also named function unit) expressed as functional group. Afterwards the energy transfer relationship among functional modules is set up, hence, the functional chain under the constraint of energy efficiency and focused function/performance is accomplished with the sub-functions replaced by functional basis.

3.2. Dividing Energy Flow Element

Functional chain describes the energy transfer relationship between functional bases. However, it does not describe design variables, interface parameters or the energy change of functional modules, so the relationship between functional modules and energy in the process of function/performance realization needs to be reconstructed by using the form of energy flow element on the basis of function chain. Generally, some functional bases with common effects on energy efficiency and performance are combined to form an energy flow element, or a functional basis can be divided into multiple energy flow elements. This process follows the flow criteria for identifying modules from functional models presented by Stone [37].

Concatenation Criterion: If the same form of energy passes through multiple sub-functions and no other forms of energy are produced, then these sub-functions can be combined into one EFE.

Parallel Criterion: If the same form of energy flow backwards through two paths at a node, these two energy flows form new energy flow respectively according to the series criteria.

Flow criteria provide a means of evaluating the correlation between sub-functions in the EFE division, but it is difficult for practical problems to find an ideal energy transfer relationship in concatenation or parallel form, therefore, using flow criteria as on its own is not enough, and it should be analyzed in conjunction with the design object.

In addition, the division of EFE should also be combined with the characteristics of products and target performance. As for the containing box of a fridge for example, when the performance constraint is its thermal load, our concern is heat loss due to the temperature difference between the inside and outside of the box. In that case, cold room and refrigerating room, though as different sub function, can be combined into one functional module, whose characteristic energy is the heat loss of the box constituted by two chambers. It should also be stressed that the flow criteria of EFE division give a method to evaluate the correlation among functional modules. However, it is improper to base this simply based on the flow criteria in the EFE division of electromechanical products;

therefore, specific design objects and performance goals need to be considered. For example, the compressor, condenser, evaporator and internal heat exchanger (IHX) can be defined as EFEs when designing a freezer refrigeration system, because their design is focused on the energy conversion and transfer when refrigerant flows through the EFEs above. The compressor manufacturer would define motor, cylinder and piston as EFEs because their focus is the conversion characteristics among electrical and mechanical energies of the compressor, and the heat energy of refrigerant.

As a basic unit of energy flow model, EFE contains function, design variables, energy variation, characteristic energy and interfaces. It is composed of one or more components and achieves function through the role of energy (flow, conversion, transformation and transfer, etc.).

3.3. Establishing Energy Characteristic Equations

After establishing EFE, characteristic energy of EFE can be calculated to evaluate the EFE's performance realization. In accordance with its definition, characteristic energy is a function of design variables and interface parameters. For energy-using electromechanical products composed of multiple EFEs, characteristic energy can be written as vector form shown in Equation (10):

$$E_c(t) = \begin{bmatrix} E_{c1}(t) \\ E_{c2}(t) \\ \vdots \\ E_{cn}(t) \end{bmatrix} = \Phi \left(\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}, q(t) \right) = \begin{bmatrix} \varphi_1(v_1, q(t)) \\ \varphi_2(v_2, q(t)) \\ \vdots \\ \varphi_n(v_n, q(t)) \end{bmatrix}, \tag{10}$$

where the vector of E_c is a function of vector v composed by design variables of all EFEs and interface state parameter $q(t)$ at time t, $E_c(t) = [E_{c1}(t), E_{c2}(t), \ldots, E_{cn}(t)]'$ is the vector composed of all characteristic energy of EFE at time t, $v = (v_1, v_2, \ldots, v_n)'$ represents design variables of all EFEs, $q(t)$ is the value of the interface state parameter at time t, and $\Phi = (\varphi_1, \varphi_2, \ldots, \varphi_n)$ is energy characteristic equation of all EFEs.

It is obvious that v and $q(t)$ are needed to calculate EFE characteristic energy. Among them, $q(t)$, which reflects the operating status of product or system at time t, is determined by initial interface state q_0 and v. q_0 is the initial value of interface state parameters, including initial conditions of interface state parameters between EFEs and boundary conditions of environment state parameters. Therefore, for a deterministic system, $q(t)$ can be obtained via v and q_0 according to system characteristics, as is shown in Equation (11):

$$q(t) = F(v, q_0), \tag{11}$$

where F is a mapping relation determined by physical characteristics of system.

If the system can be described by physical characteristic function, $q(t)$ can be solved by numerical calculation based on analytic equation or finite element method. In addition, if this is not the case, then $q(t)$ can be solved by experiment or regression approximation. Furthermore, the two methods above can also be combined. Under the conditions of the v and q_0, the characteristic energy of each EFE can be obtained by Equations (10) and (11).

Afterwards, the EFE model contains the physical relationship between various parameters in the form of mathematical equations, which provides quantitative support for the analysis of the system model and can be the basis of a specific parameter analysis of performance design. As for the EFE of a household refrigerator compressor (Figure 4), its characteristic energy (W_{com}), which is compression work of the compressor to convert electrical energy into refrigerant heat, is described as Section 2.4.

Based on the energy characteristic equations of compressor in Equation (3), the interface state parameters ($p_{r,in}$, $p_{r,out}$) are defined as the test condition national standard value (63 kPa, 762 kPa). According to the design variables in Table 2, the characteristic energy W_{com} of compressor EFE in stable operation is 55.7 W. Thus, characteristic energy contributing to realizing EFE function can be quantified with energy characteristic equations.

Table 2. Design variables of a type of compressor.

Design Variables	Parameters
V_{th} (cm^3)	9.05
N (r/min)	3000
η_v	0.8275
η_i	0.7219

3.4. Performance Design Based on Energy Flow Model

Through energy flow analysis, the link of EFEs that contains design parameters, interface information, characteristic energy and performance parameters will effectively enhance the logical and causal relationship between parameters in product performance analysis. Furthermore, based on the energy flow model, the simulation and analysis algorithm of product can be designed to quantitatively analyze the relationship between performance parameters and design parameters. This will be shown in the case study in Section 4 as well.

As is the key to the performance response via energy consumption of energy-consuming electromechanical products, energy is strongly related to energy efficiency and performance. After establishing the energy flow element reflecting the energy action form and state and the characteristic energy used to evaluate the impact of EFE on performance realization, a performance design process for analyzing the impact of component design variables on energy flow and performance was constructed based on the energy flow model, as is shown in the Figure 10.
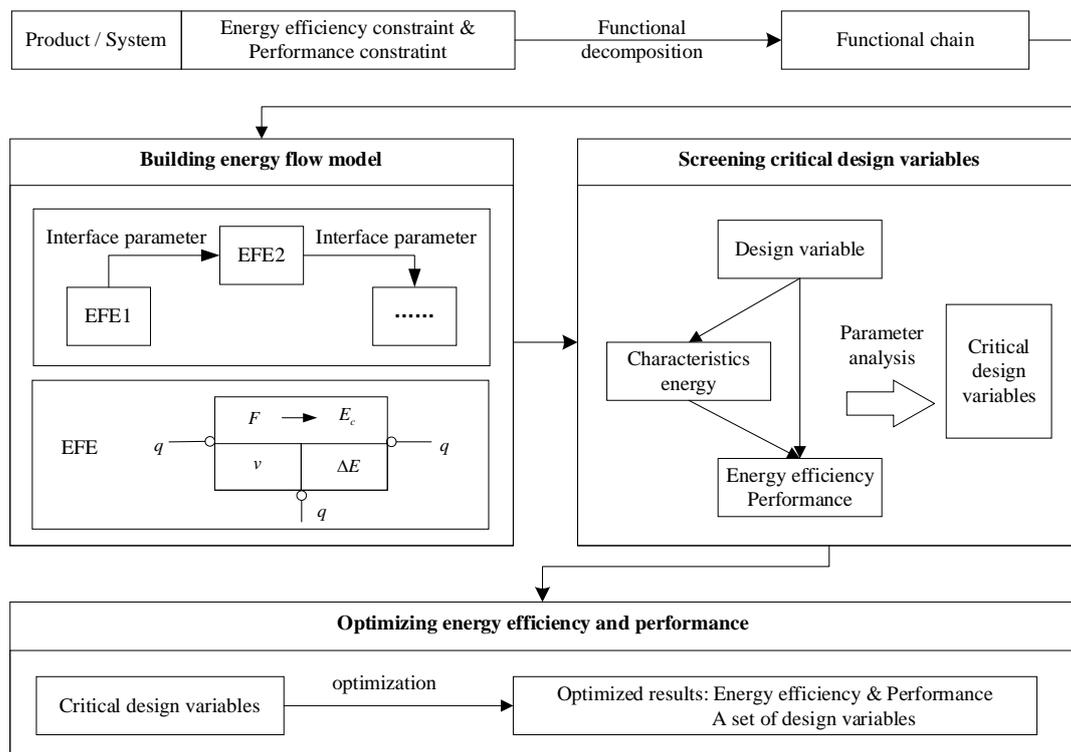
Figure 10. Performance design procedure based on energy flow model.

The performance design process based on energy flow model is mainly to construct the relationship among design variables, characteristic energy and energy efficiency/performance to support product performance design. Firstly, a functional chain was built by function decomposition under the constraints of energy efficiency and performance. Then, an energy flow model based on EFE was established according to the above

modelling procedure. Through an analysis of the relationship among design variables, characteristic energy and performance supported by EFE model, combined with numerical simulation and CAE analysis, the simulation model was established. The critical design variables are screened with the working characteristics of product or system and operation state parameters under different design variable combinations simulated based on the simulation model. Lastly, energy efficiency improvement and performance enhancement could be accomplished by optimizing the critical design variables.

4. Example Applied to Refrigerator

In order to verify the effectiveness of the energy flow model for energy efficiency improvement, an air-cooled refrigeration system was taken as an example for comparative analysis of simulation and test.

4.1. Energy Flow Model of Refrigerator

A refrigerator is a kind of product which insulates heat through thermal insulation materials to preserve objects at low temperature with the principle of steam compression for refrigeration. In the refrigeration system of a refrigerator, refrigerant is used as the medium to transport energy among parts and components. There are several forms of energy such as electrical energy, mechanical energy, heat energy, etc. Furthermore, the structure consists of mechanical parts, heat exchangers, throttling elements and other energy action forms, which all have great complexity.

The specific refrigeration process is demonstrated in Figure 11. Low-temperature low-pressure gaseous refrigerant (R600a) flows into the compressor from the air suction tube (point 1) and is compressed into high-temperature, high-pressure gas (point 2). Then, it is cooled into high-pressure supercooled liquid (point 3) with heat released outward through the condenser. After that, it turns into a low-temperature, low-pressure, two-phase liquid (point 4) after flowing through the internal heat exchanger combined with capillary tube and suction tube. It then evaporates into low-temperature, low-pressure gas (point 5) by absorbing heat in the evaporator. Finally, it turns into low-pressure, superheating gas by transferring heat with a capillary tube (point 1) in a suction tube, thus a vapor compression refrigeration cycle is completed. In the meantime, the evaporator constitutes air circulation system with the refrigerator cabinets through the air duct system to provide cooling capacity for the refrigerator cabinets to realize the low-temperature storage function of the refrigerator.

Note: point 1~5 represented the interface parameters check point of each components.
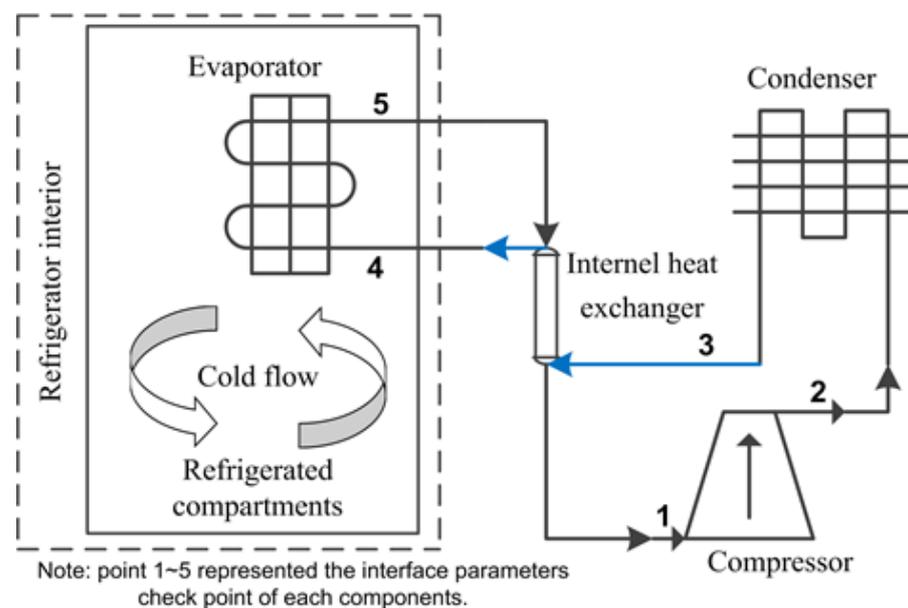
Figure 11. Refrigeration principle of refrigerator.

Since refrigeration performance and energy consumption are the key performances of refrigerator design, the refrigerating capacity, as well as energy efficiency, were set as the constraints to analyze the energy flow of a refrigerating system.

In functional analysis, our focus is on the function involving energy conversion of the refrigerant, so some functions unrelated to the performance design of the refrigeration system will not be considered in the functional chain, such as opening and closing of the refrigerator door, some additional functions of the chamber (keeping fresh, moisturizing, degerming, anti-microbial, lighting, etc.), multimedia, compressor noise reduction, the defrosting function and so on. Excluding those functions, the refrigerator functions based on the refrigeration principle of the refrigerator are summarized as the functional chain shown in Figure 12.
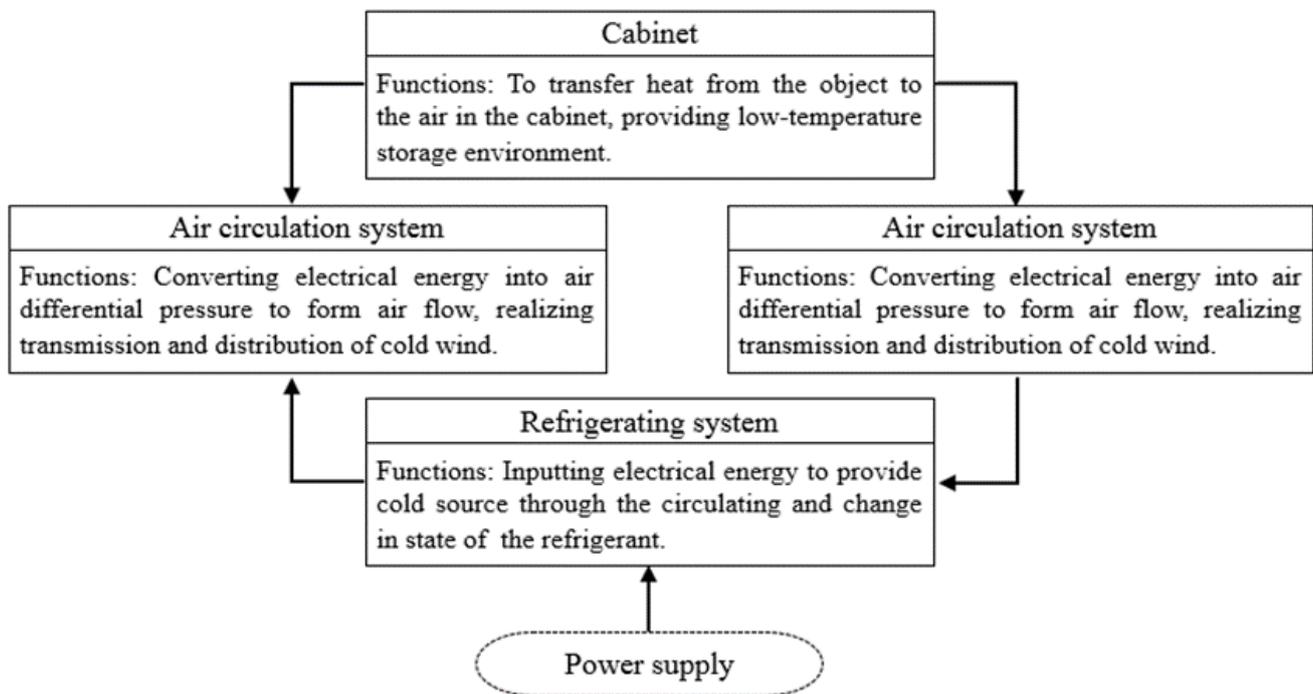
Figure 12. Summarized functional chain of refrigerator.

The functions of the subsystem are decomposed until we reach the bottom of the function tree and the functional chain is detailed with energy conversion or transfer function. Expressing sub-functions in common functional basis and establishing the energy transfer relationship between the functional basis, Figure 13 depicts the functional chain of the refrigerator.

According to flow criteria, the correlation among functional modules in Figure 14 can be obtained by analyzing the functional chain of a refrigeration system shown in Figure 13. In Figure 14, there is heat transfer between FB3 and FB4, in other words, they are in series relation and can be combined into an EFE (refrigerator cabinet). FB5 and FB6 are related through air and heat, which satisfies the series rule. Considering the design object, there is a structural assembly relationship between component of FB5 (air flue) and component of FB6 (fan), that is, the effect of energy can be analyzed with the uniform method of flow field. Therefore, they can be combined into an EFE. FB7 to FB11 are related through refrigerant, which satisfies the series rule. FB7 to FB11 can be also combined into an EFE in principle, however, those components (compressor, condenser, evaporator, IHX) have significant influence on refrigeration performance, and thus they are not merged here. Consequently, the functional chain of a refrigerator under the constraints of refrigerating capacity and energy efficiency is divided into six functional modules (compressor, condenser, evaporator, IHX, air duct system and refrigerator cabinet), as is

shown in Figure 15. These can be respectively converted into EFEs including functions, design variables, interface parameters, characteristic energy, etc.
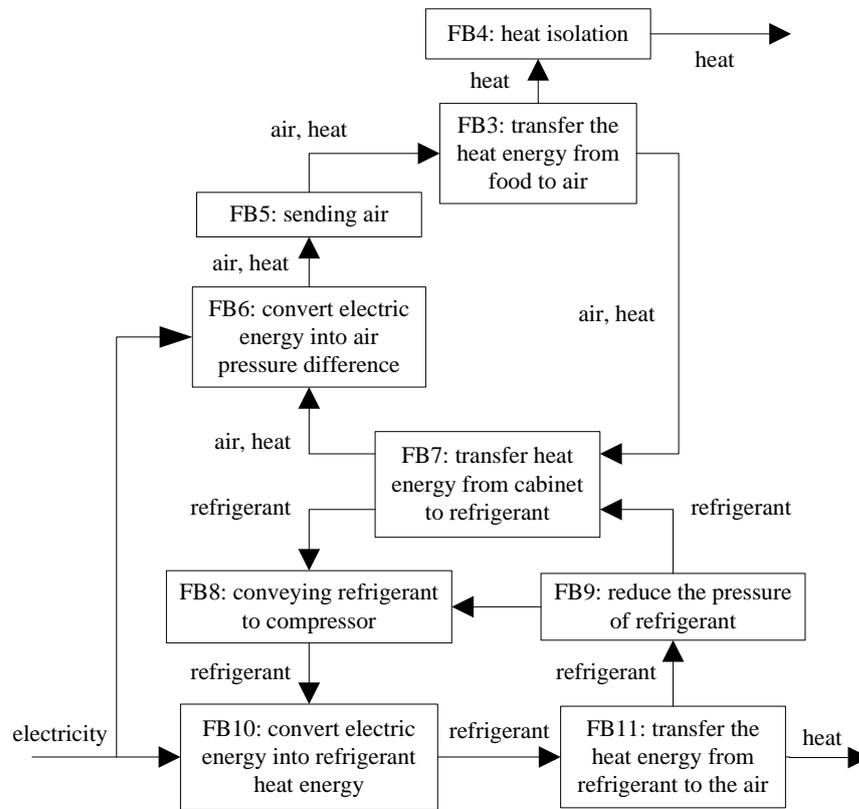
Figure 13. Functional chain of refrigerator under the constraint of refrigerating capacity and energy efficiency.
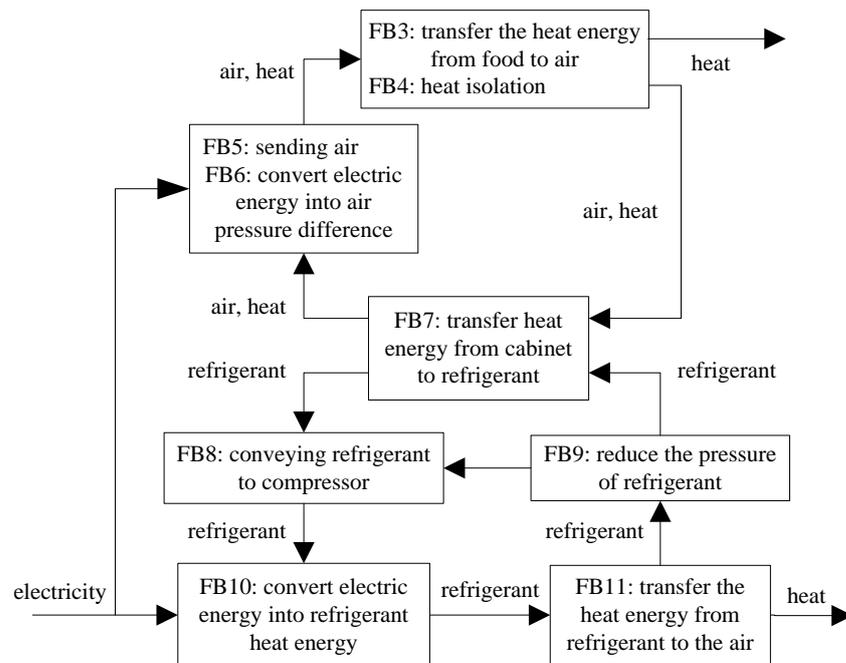
Figure 14. The correlation among functional modules of a freezer refrigeration system based on flow rule.
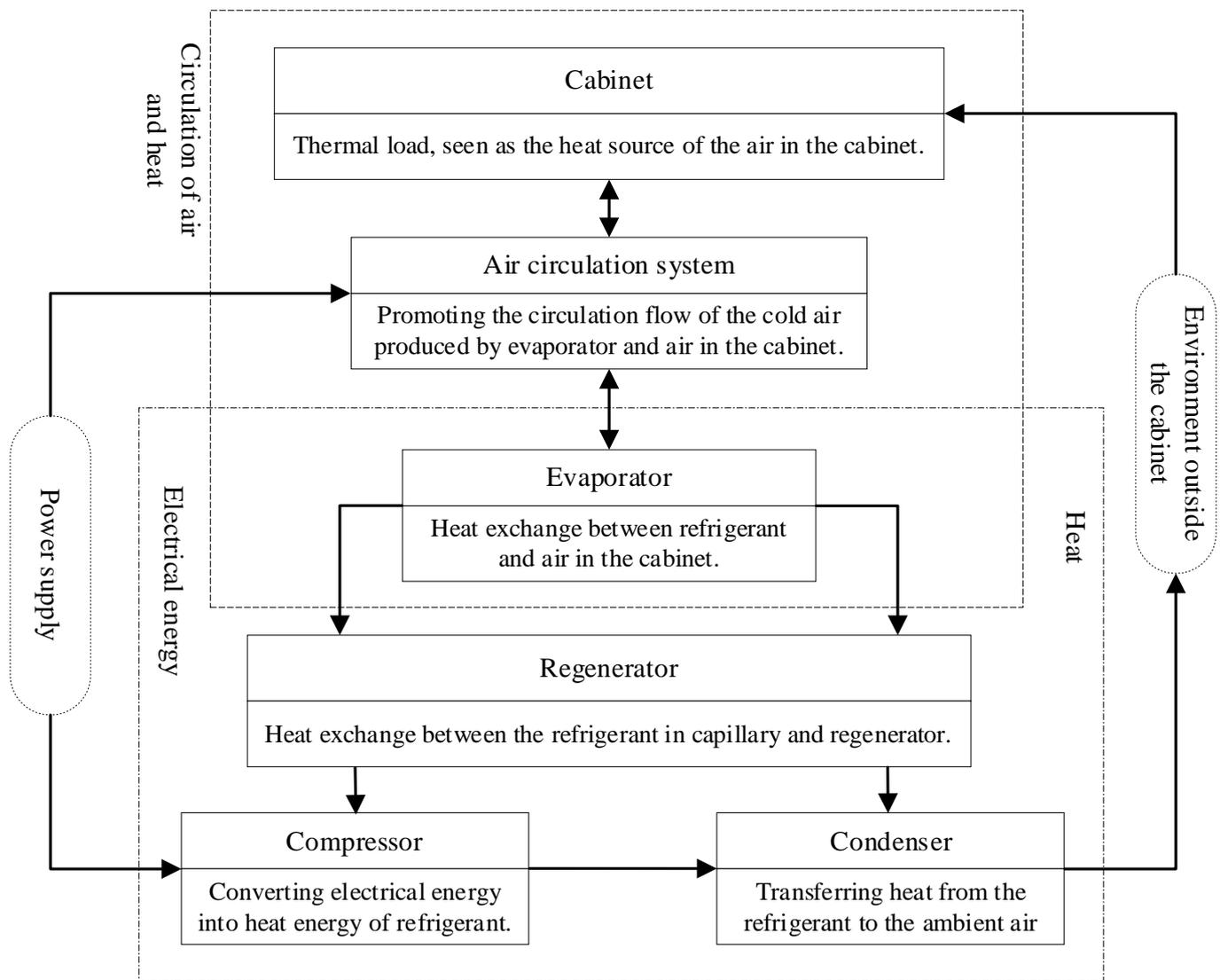
Figure 15. The functional modules of refrigeration system.

Parsing of each function module according to the principle of EFE, EFE model is set up with function information, energy flow information, design information and performance information. The physical relation among characteristic energy, design variables and interfaces are also analyzed in the form of characteristic equations.

Design variables and interface parameters of six EFEs are shown in Table 3. Characteristic energy and its expression are shown in Table 4.

Table 3. Parameters of refrigerating system model.

EFE	Design Variables	Input Parameters	Output Parameters
Compressor	$T_a, N, V_k, \eta_v, \eta_g, UA_k$	P_{cond}, h_1, P_{evap}	h_2, T_2
Condenser	$l_{cond}, m_a, m_r, d_i, S_r$	T_2	T_{cond}, P_{cond}
IHX	$\Delta T_{sc}, \Delta T_{sh}, \varepsilon_{ihx}$	T_{cond}, T_{evap}	h_1, h_4
Evaporator	$l_{evap}, m_a, m_r, d_i, S_r$	h_4, T_{cab}	$T_{evap}, P_{evap}, Q_{evap}$
Compartments	$W_{ef}, UA_{ff}, UA_{fz}, T_{ff}, T_{fz}, m_{ef}$	Q_{evap}	T_{cab}
Air duct system	$W_{fan,p}, \eta_f, C_{pa}$	T_{evap}	$M_a, E_{fan}, T_{cab,in}$

Table 4. Characteristic energy and its expression.

EFE	Characteristic Energy	Description of Characteristic Energy	Energy Characteristic Equation
Compressor	W_{com}	Compression work	$W_{\text{com}} = m_{\text{r}} p_{\text{in}} v_{\text{in}} \frac{\kappa}{\kappa-1} \left[\left(\frac{p_{\text{out}}}{p_{\text{in}}} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right] / \eta_{\text{i}}$
Condenser	Q_{cond}	Heat transfer from condenser to the air	$Q_{\text{cond}} = (T_{\text{w}} - T_{\text{air}}) U_{\text{o}} A_{\text{o}} = m_{\text{r}} (h_{\text{in}} - h_{\text{out}})$
IHX	Q_{IHX}	Heat transfer from capillary to air suction pipe	$Q_{\text{IHX}} = m(h_{\text{SL,out}} - h_{\text{SL.in}}) = m(h_{\text{cap,in}} - h_{\text{cap,out}})$
Evaporator	Q_{evap}	Heat transfer from air in cabinet to evaporator	$Q_{\text{evap}} = (T_{\text{cab}} - T_{\text{w}}) U_{\text{o}} A_{\text{o}} = m_{\text{r}} (h_{\text{out}} - h_{\text{in}}) = (T_{\text{w}} - \overline{T}_{\text{r}}) U_{\text{i}} A_{\text{i}}$
Compartments	Q_{cab}	Heat transfer from food to air in cabinet	$Q_{\text{cab}} = U_{\text{food}} A_{\text{food}} (T_{\text{food}} - T_{\text{cab}}) = m_{\text{air}} (h_{\text{air,out}} - h_{\text{air,in}})$ $- U_{\text{cab}} A_{\text{cab}} (T_{\text{env}} - T_{\text{cab}}) - W_{\text{fan}}$
Air duct system	W_{fan}	Fan electric power	$W_{\text{fan}} = E_{\text{fan}} = E_{\text{air,out}} - E_{\text{air,in}} = \Delta p_{\text{air}} \cdot Q_{\text{V,air}}$
	ΔE_{tube}	Energy change of cold air flow in the air duct	$\Delta E_{\text{tube}} = E_{\text{air,in}} - E_{\text{air,out}} = E_{\text{loss}}$

The purpose of energy flow model is to support performance design by connecting performance and relevant design variables under energy efficiency and performance constraints with energy being a bridge. The detailed process of how a compressor EFE model is established is shown in Section 2.2. In addition, energy flow analysis of other functional modules, and establishment of other EFEs, are similar. Combining EFE model and functional chain, an energy flow model of the refrigeration system under energy efficiency and refrigerating capacity is shown in Figure 16.
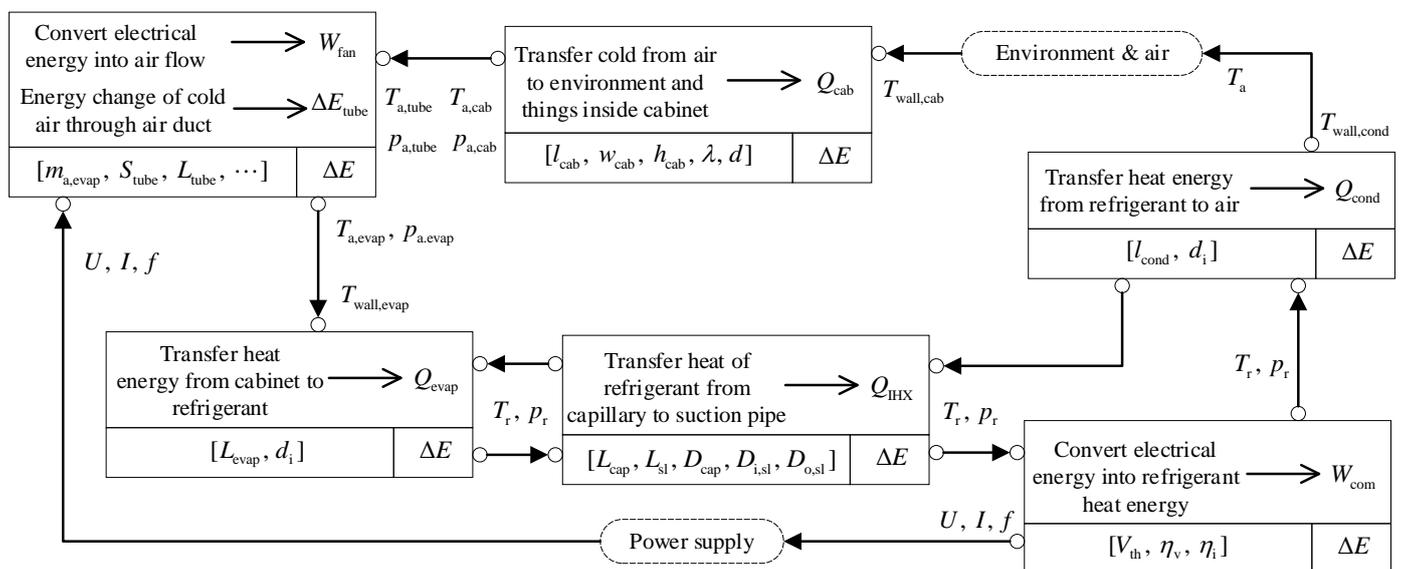
Figure 16. Energy flow model of refrigerator refrigerating system.

4.2. Simulation and Validation of Refrigerator

The test refrigerator is an air-cooled refrigerator BCD-4XX with a refrigeration cabinet and a freezing cabinet as is shown in Figure 17.
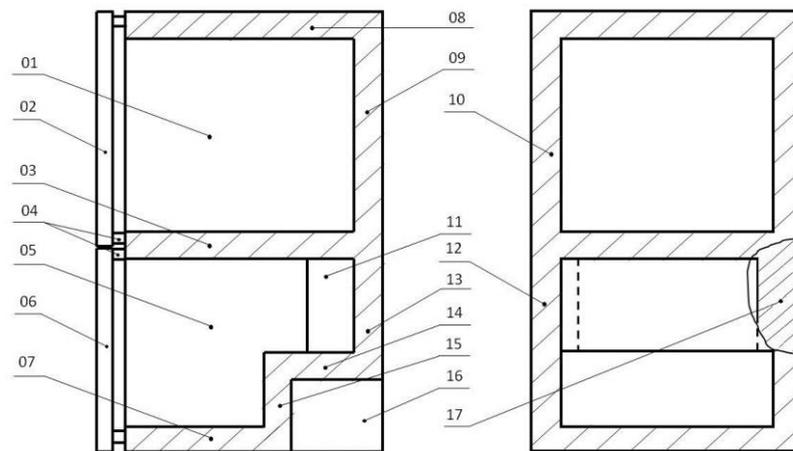
Figure 17. Structural diagram of refrigerator prototype box. 01 Refrigeration cabinet; 02 door of refrigeration cabinet; 04 door gasket; 05 freezing cabinet; 06 door of freezing cabinet; 11 evaporator chamber; 16 compressor chamber; 03/07~10/12~15/17 thermal-protective coating.

Based on the energy flow model of the refrigerating system, a simulation iterative process of refrigeration performance on account of EFE was built for this paper, as is shown in Figure 18. The refrigerator running state is described by the energy flowing among EFEs and the energy is represented by the thermodynamic enthalpy for the refrigerator's refrigeration performance. In order to determine whether the refrigerator is running in steady state, the target temperature of compartments, condenser and evaporator are chosen as criterion parameters in the simulation iterative process. Once an iteration is completed, the refrigerator is considered to be in a stable state. Performance index parameters and corresponding design parameters which can support simulation analysis for performance matching are the outputs of the program. Moreover, the characteristic energy is also calculated in the results and can be used to evaluate realization of function and performance.
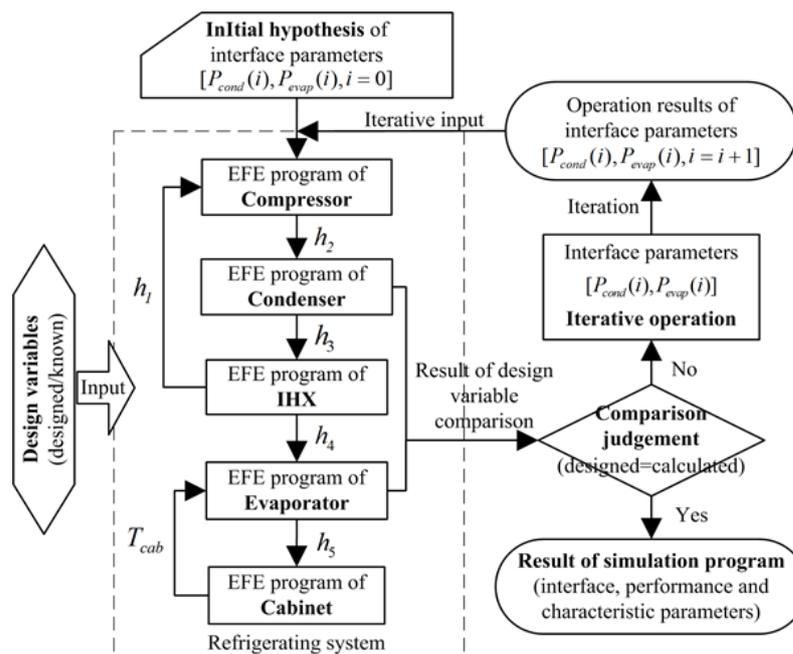
Figure 18. Iterative process chart of refrigerating performance simulation based on energy flow model.

For a refrigerator, usually evaporating temperature, condensation temperature, inlet temperature of refrigeration cabinet and freezing cabinet are the key performance indicators, while day-power consumption, operating rates and energy efficiency ratio constitute the most important indicators of energy efficiency. In order to confirm the effectiveness of an energy flow model through experiments, the above-mentioned indicators are chosen as the judgment parameters to verify the validity in product design and energy efficiency.

A test bench for the refrigerator was built and tested at room temperatures of 16 °C and 32 °C, respectively. The system arrives at a steady state after 600 min. The calculated value obtained through refrigeration simulation process and the measured value of parameters are recorded in Table 5.

Table 5. Comparison of measured value and calculated value.

Indicators	16 °C			32 °C		
	Calculated Value	Measured Value	Error	Calculated Value	Measured Value	Error
Evaporation Temperature (°C)	−29.82	−27.00	2.82	−26.34	−26.00	0.34
Condensation Temperature (°C)	35.30	32.50	2.80	52.66	48.00	4.66
Refrigeration Cabinet Inlet Temperature (°C)	1.53	2.50	0.97	0.04	3.25	3.21
Freezing Cabinet Inlet Temperature (°C)	−24.64	−21.94	2.70	−24.62	−21.34	3.28
Day-power Consumption [(kWh/day)]	0.65	0.56	0.09	1.38	1.26	0.12
Operating Rate ($R/\%$)	50.8	50.0	0.8	83.2	93.0	9.8

As is shown in Table 5, the temperature deviation between calculated value and measured value is within five degrees and the deviation of day-power consumption, operating rates and energy efficiency ratio is generally less than one generally. Thus, it is proved that the proposed analysis method of energy flow model has reliable precision in the application of performance response to design variables and can be used for energy characteristic analysis and performance design of the refrigerator.

4.3. Example of Energy Efficiency Improving and Performance Design

Accurate calculation about the performance response to design variables based on energy flow model contributes to the obtaining of a quantitative relation between design variables and performances instantly. However, performance optimization and energy efficiency improvements are complex processes with different influences on various design variables with different performances. This means that a clear relationship needs to be studied, which is the following use of an energy analysis of energy flow model.

The performance-matching method based on the energy flow model is illustrated with the following example for a certain 265 L refrigerator whose daily electricity consumption is 0.6958 kW·h/24 h.

Firstly, the performance objectives and constraints of a power-saving refrigerator were defined. According to the user demand and the quality standard that the product should meet, the performance requirements of the refrigerator include three aspects: a power saving and consumption reducing characteristics, a food preservation characteristic and a running state characteristic. Specific indicators are described as follows:

1. The characteristic of power saving and consumption reduction is closely related to daily electricity consumption EC_{day} (kW·h/24 h). The parameter can be used to evaluate energy consumption of refrigerator and is an important reference index for the calculation of an energy efficiency index in the energy efficiency labeling system implemented in China since 2015.

2. Food preservation characteristics include temperature accuracy and uniformity of temperature space. The temperature accuracy is mainly related to the choice and accuracy of a temperature control system, while the uniformity of the temperature space is related to the energy effect of the refrigeration system EFE and air circulation EFE. Therefore, the energy-related temperature uniformity is the focus of this paper. The temperature uniformity is related to the temperature distribution in the refrigerator and can be reflected by the statistical standard deviation of different sampling points. To be consistent, the reciprocal σ_T^{-1} (°C^{-1}) of standard deviation is used in the following analysis so that larger σ_T^{-1} indicates better temperature uniformity.

3. The running state characteristic mainly includes operating rate. Operating rate is equal to the ratio of refrigeration time to cycle time in a refrigeration cycle. It is an important indicator reflecting the matching characteristics of a refrigeration system and box. If the operating rate is too high, the compressor starts frequently, which will cause great starting loss to the fixed-frequency compressor. If the operating rate is too low, the compressor has a large power and a large starting torque, which may damage the internal structure of the compressor. A reasonable operating rate should be the tradeoff between cooling rate and startup time.

In order to reach the requirement of energy efficiency and concerned performance above, a performance matching problem can be solved by optimizing critical design variables which have significant influence on the concerned performance. The critical EFE design variables are screened by analyzing the effect of EFE design variables on characteristic energy and performance, combining with engineering practice.

Based on the energy flow model and its simulation model in Sections 4.1 and 4.2, the influence of EFE design variables on characteristic energy and performance are calculated and analyzed by taking theoretical volumetric capacity of compressor EFE as an example.

The influences of compressor theoretical volumetric capacity V_{th} on each EFE characteristic energy and performance are calculated via steady-state performance simulation of the refrigeration system and are shown respectively in Figures 19 and 20. As is seen in the figures, theoretical volumetric capacity has a great influence on EC_{day} and R. With theoretical volumetric capacity increasing, the performance of all EFEs is improved while the efficiency of the whole machine decreases, which leads to a significant increase in power consumption. That is, although the increase of theoretical volumetric capacity leads to the decrease of the operating rate, the day-power consumption of electricity still increases.
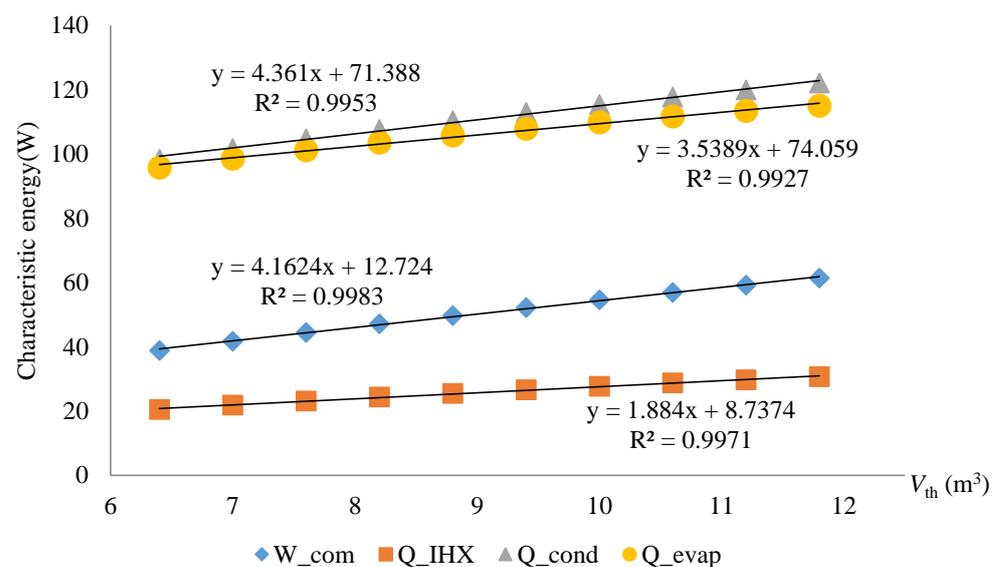
Figure 19. The influences of compressor theoretical volumetric capacity on EFE characteristic energy.
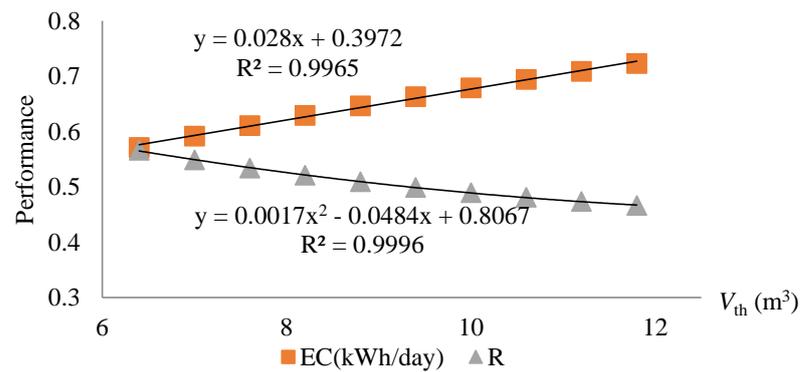
Figure 20. The influences of compressor theoretical volumetric capacity on performance parameters.

The analysis about the influences of other EFE design variables on characteristic energy and performance is similar to that of the compressor theoretical volumetric capacity. Based on these parameter analysis results, five design variables which have a significant influence on characteristic energy and performance, and which are easy parameter modifications to realize were selected. In addition, according to the effect trend, engineering experience and manufacturing process, the parameter scope of five design variables were set and are shown in Table 6. The five design variables included compressor theoretical volumetric capacity V_{th}, refrigerant charge M, length of capillary tube L_{cap}, length of evaporator tube L_{evap} and air volume of fan m_a.

Table 6. Parameter scope of five design variables.

| Serial Number | Design Variables | | | | |
	V_{th} A/cm^3	M B/g	L_{cap} C/m	L_{evap} D/m	m_a E/kg·s^{-1}
1	8.34	41	2.4	5.7	0.024
2	8.56	41.3	2.5	6.0	0.026
3	8.75	41.7	2.6	6.2	0.028
4	9.05	42	2.7	6.5	0.030
5	9.27	42.3	2.8	6.7	0.032
6	9.56	42.6	2.9	7.0	0.034
7	9.78	43	3.0	7.2	0.036

A uniform design method was adopted to obtain the performance response of each group with the simulation model, as is shown in Table 7.

Table 7. Performance response of each group with simulation model.

| Test Number | Design Variables | | | | | Performance Response | | |
	A	B	C	D	E	σ_T^{-1}	EC_{day}	R
1	1	2	3	4	6	2.64	0.6270	71.17
2	2	4	6	1	5	2.53	0.6271	70.56
3	3	6	2	5	4	2.44	0.6264	69.98
4	4	1	5	2	3	2.35	0.6281	69.32
5	5	3	1	6	2	2.27	0.6279	68.73
6	6	5	4	3	1	2.19	0.6290	68.10
7	7	7	7	7	7	2.67	0.6610	68.99

With daily power consumption as the design objective and other parameters as the performance constraints ($R \leq 70\%$, $\sigma_T^{-1} \geq 2.5$ $^{\circ}C^{-1}$), a regression model between design variables and performance response was established. The mixed integer linear programming method was adopted to calculate the results satisfying the optimization conditions

as follows: V_{th} = 9.27 cm^3, M = 41 g, L_{cap} = 2.4 m, L_e = 5.7 m, m_a = 0.024 kg/s. The corresponding performance response was calculated by simulation: EC_{day} = 0.6192 kW·h/24 h, R = 69.91%, σ_T^{-1} = 2.57 °C^{-1}. The product with EFEs corresponding to the results was tested and the improved test results are shown in Table 8.

Table 8. Improved test results of the product with EFEs.

Performance Index	Test Result
Daily electricity consumption EC_{day} (kW·h/24 h)	0.6327
Temperature uniformity σ_T^{-1} (°C^{-1})	2.52
Operating rate R (%)	68.0

In Table 8, the difference between improved test data and simulation data may result in heat leakage and eddy currents caused by delicate structure. In spite of this, the performance matching optimization design of the improved prototype still meets the requirements of the optimization problem among which the daily power consumption is reduced by about 9%. Therefore, the performance matching and energy efficiency increasing method based on energy flow model is effective and provides a direction for the optimization and design of design parameters supporting energy efficiency improvement.

5. Conclusions

As the key factor in realizing functions and performance with consumption of power, energy plays a significant role in the design process of performance and energy efficiency improvement for complex electromechanical products. The main aim of the present study was to improve energy efficiency with energy as a bridge between design variables and performance. The most important outcomes are summarized as follows:

- Energy flow model with basic element EFE was proposed and built based on functional basis. The model contains function, design variable and characteristic energy in EFE, the interface parameter between EFEs and the environment, which can support the design of performance and energy efficiency improvement.
- The modelling process of the energy flow model under the constraints of energy efficiency and target performance was presented. This contains the building of a functional chain under the constraints of energy efficiency and performance, division of EFE, building energy flow model and calculation of characteristic energy.
- The performance and energy efficiency design procedure based on energy flow model was presented to systematically and logically describe the interactional and anfractuous relationship between performance and design parameters, thereby supporting a detailed design using as bases the characteristic energy and energy characteristic equations with the energy flow model.
- The energy flow model of the refrigerator, containing six EFE models (compressor, condenser, IHX, evaporator, compartments and air duct system), under the constraints of refrigerating performance and energy efficiency improving was built.
- Based on the operating principle of a refrigerator system and the energy flow model, a simulation iterative process of refrigerating system performance was presented, and the effectiveness of the model was verified by a comparison between simulation and experiment.
- The performance matching method based on the energy flow model was illustrated with an example for a certain 265 L refrigerator. There were five critical design variables screened, containing V_{th}, M, L_{cap}, L_{evap} and m_a. With EC_{day} as design objective and σ_T^{-1} and R as performance constraints ($R \leq 70\%$, $\sigma_T^{-1} \geq 2.5$ °C^{-1}), the optimization results of five critical design variables are as follows: V_{th} = 9.27 cm^3, M = 41 g, L_{cap} = 2.4 m, L_e = 5.7 m, m_a = 0.024 kg/s. The corresponding calculation results calculated by energy flow simulation model are: EC_{day} = 0.6192 kW·h/24 h, R = 69.91%, σ_T^{-1} = 2.57 °C^{-1}, while the test results of improved prototype are: EC_{day} = 0.6327 kW·h/24 h, R = 68.0%,

σ_T^{-1} = 2.52 °C^{-1}. The test results of the improved prototype meet the requirements of operating rate and temperature uniformity, and the daily electricity consumption is reduced by about 9%. The comparison between design results of energy flow model and testing results of refrigerator prototype validate that the performance matching and energy efficiency increasing method based on energy flow model is effective.

In the last decades, there have been many methods to support product design and energy efficiency improvement based on energy. Some of these, such as functional basis and bond graph, have been presented during the conceptual design stage and cannot be applied to the detailed design stage since none of these quantitatively developed a relationship among design variables, energy flow and performance. While other methods based on energy during the detailed design stage tended to improve energy efficiency within the limited scope of parts design, or under a single performance constraint. In our paper, we attempted to link the conceptual design and detailed design with an energy flow model which contributes to ascertaining how various design variables impact the response of energy efficiency and performance to instantly support performance matching. Therefore, the energy flow model is conducive to support energy efficiency improvement at the product or system level.

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