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# Simulation technology for refrigeration and air conditioning appliances

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**Abstract** Simulation technology has been widely used for performance prediction and optimal design of refrigeration and air conditioning appliances. A brief history of simulation technology for refrigeration and air conditioning appliances is reviewed. The models for evaporator, condenser, compressor, capillary tube and thermal insulation layer are summarized, and a fast calculation method for thermodynamic properties of refrigerant is introduced in this paper. The model-based intelligent simulation technology and the simulation technology based on graph theory are also illustrated. Finally, an updated trend of simulation technology development for refrigeration and air conditioning appliances is discussed.

**Keywords: refrigeration, air conditioning, simulation, model, computer.**

The output of refrigeration and air-condition appliances have been increasing rapidly in recent years, especially in China. For example, the annual output of room air conditioners in China is over two thirds of the world total, and the use of air conditioners consumes a lot of electricity, amounting up to 40% of the total electricity consumption in the summer in some cities like Shanghai. Therefore it is an important target to make the design process of refrigeration appliances more efficiently and to improve the product performance. Computer simulation technique is one of valuable means to accomplish this target[1−3].

The traditional methods for designing refrigeration and air-conditioning appliances are: to determine the required performance object of a product at first, then to estimate the working conditions, and to calculate the structural parameters at last. This process is very straightforward and quite easy to be understood. But the actual performance of the product might obviously deviate from the required one because there is no accurate model available in the design process. In order to let the products have the desired performance, the processes of developing prototypes, testing their performance and modifying their structures have to be repeated many times, which will increase the cost and delay the completion of the design process.

With the computer simulation method, the working conditions and the structural parameters of the product are given, and then the performance is predicted. After predicting the product performance by simulation, the configuration parameters of the product can be evaluated easily. In order to get a group of suitable configuration parameters of the product, the original parameters should be adjusted according to the simulated results, and simulation with the adjusted structural parameters will be done again. The process of modifying the parameters and simulating with modified parameters will be repeated many times until a set of the most suitable parameters is obtained. Such a computation process is an optimization process, which can be implemented by adding some optimization programs or directly operated by users based on their experience. In order to obtain a perfect optimization result quickly, the initial parameters should not be far away from the optimal ones. It is recommended to give the appropriate parameters for optimization with a conventional design method.

Researchers, such as Dhar & Soedel[4], Chi & Didion[5], began to do refrigeration and air-conditioning appliance simulation at the end of the 1970s and the beginning of the 1980s. Many papers[5−13] on modeling of refrigeration and air-conditioning appliances were published in the 1980s. Lots of simulation technologies were used to substitute CFCs since the late 1980s[14−20]. Artificial intelligence technologies[21−24] and graph theory[25] were introduced into simulation of refrigeration and air-conditioning appliances at the end of the 1990s, which further enriched the simulation methods.

In this paper, the state-of-art of simulation technology for refrigeration and air-conditioning appliances is reviewed and the trend of simulation technology for refrigeration and air-conditioning appliances is discussed.

## 1 Mathematical model for main components of refrigeration system

The cycle system for realizing the basic function of refrigeration is called refrigeration system, which includes four main components, i.e. compressor, evaporator, condenser and throttling device. Here, evaporator and condenser can be treated as a heat exchanger. The throttling device can be expansion valve, capillary tube, orifice tube, etc. Capillary tubes are widely used in the small-scale refrigeration and air-conditioning appliances, a large amount of production, and there are a lot of papers on capillary tube modeling. This paper chooses the capillary tube as the representative of throttling devices.

### *1.1 Compressor model*

Compressor is the power source to drive the entire refrigeration system. Different heat and mass transfer and mechanical movements can be observed for different types of compressors in the running process. So different kinds of mathematical models should be developed depending on the objectives of the study[26,27]. In the refrigeration system simulation, the important performance parameters are refrigerant mass-flow rate, input power and the refrigerant temperature at the compressor exit. Some unimportant parameters can be ignored in order to simplify the model.

Compressor models for refrigeration system simulation includes following types.

(1) Dynamic model

The actual operating characteristics of compressor are always dynamic even in a stable running condition. For example, the refrigerant mass-flow rate of a reciprocating compressor varies in each cycle of the compressor motor. Therefore a dynamic model reflecting the dynamic characteristics of all parts of the compressor might be more accurate than a steady state model, and such models were used for dynamic simulation of refrigeration systems[5]. But this kind of dynamic model is complicated, and the calculation speed is slow. We believe such a model is suitable for simulation or optimum design of compressors but not suitable for simulation of refrigeration systems.

(2) Steady state model

This model is introduced to calculate thermodynamic compressor performance in text books[1]. Once the calculation method with the (semi-) empirical parameters for polytropic exponent, mass-flow rate coefficient and motor efficiency are determined, the calculation of the compressor performance becomes explicit and very fast. This kind of compressor model was used in some earlier works by Murphy [8] and MacArthur[9].

A steady state compressor model is certainly suitable for a steady simulation of a refrigeration system. In simulating the mass-flow rate of refrigerant through compressor in the dynamic simulation of refrigeration systems, a steady state model can still be used because the time constant of refrigerant flow-rate variation is too small compared to that of the heat exchangers. But for the start-up process of the compressor when the rotating speed of the compressor varies from 0 to its full rotation speed, the simulation accuracy and the stability can be improved if we use a zero-order or one-order delay model instead of a steady state model.

The time constant for the heat exchange process in compressor is large because of the large heat capacity of the compressor. So the calculated temperature inside the compressor might not be accurate enough if a steady state model is used.

(3) Two-node model

This model may be divided into two parts: steady state model for the mass flow rate calculation and dynamic model for the calculation of heat exchange process[1,13]. This model is recommended for dynamic system simulation.

### *1.2 Capillary tube model*

Experimental and theoretical studies on capillary tube began in the 1940s[28,29]. Different models and algorithms have been developed to meet different requirements with different refrigerants.

(1) Models for different refrigerants

Researches, especially experimental researches on capillary tubes, have close relations to the working fluids. A lot of earlier studies have dealt with refrigerants R12[30−32] and R22[33−35]. But at present, more researches focus on CFCs alternatives, such as pure refrigerants of R134a and R152a[36−42] and blended refrigerants of R410A and R407C[43−45].

(2) Adiabatic and nonadiabatic capillary tubes

The speed of the refrigerant flowing through the capillary tube is very fast and the order of magnitude of time for refrigerant flowing through a capillary is 0.1 s. The outside heat transfer surface area of a capillary tube is small because of its very small diameter. The flow in the insulated capillary tube can be considered as an adiabatic flow. If the capillary tube is directly exposed to the ambient air, just like those in the room air conditioners, the incoming flow can still be considered as an adiabatic flow because the natural convection heat transfer on the outer surface of the capillary tube is small. A lot of studies on adiabatic capillary tube have been published[38,40,45,47−57].

When the capillary tube is combined to the suction tube to make a regenerator, as is often done in household refrigerators, the heat transfer will influence the refrigerant mass-flow rate, and the capillary tube under this condition belongs to non-adiabatic capillary. A non-adiabatic capillary tube can be treated as an equivalent adiabatic capillary tube in the calculation of the refrigerant mass-flow rate for engineering applications[42]. But this equivalent method lacks theoretical proof. As there are some differences in the characteristics between adiabatic capillary tubes and non-adiabatic capillary tubes, further studies on models and solutions for the non-adiabatic capillary are necessary[41,42,58−62].

For the adiabatic capillary tube, the quality of two-phase refrigerant will increase in the flow direction. An actual non-adiabatic capillary tube has similar characteristics. But in the calculation, the two-phase refrigerant might return to subcooled section in the flowing direction due to the outside heat transfer effect, and then calculation instability will occur. One of the solutions to this sort of calculation problem is to assume a linear distribution of the refrigerant quality in the two-phase region[59].

(3) Distributed parameter model for capillary tube

The most important type of capillary tube model is a distributed parameter model. Most of distributed parameter models belong to homogenous equivalent model (HEM). The assumptions in HEM include thermodynamic equilibrium, nil slip and complete mixing between liquid phase and vapor phase.

The metastable flow occurs due to high speed of refrigerant flowing through the capillary tube[31,63−67]. Metastable flow is sensitive to working conditions and it is difficult to observe in experiments[33]. Chen's correlation[31] is one of the best empirical correlations for metastable flow, but it still has obvious deviations[33,34]. Due to the effect of the metastable flow, the refrigerant mass-flow rate in capillary is not only affected by the working conditions, but also by the way to reach this condition[58,65]. That is to say, there might exist two values of refrigerant mass-flow rate under the same working condition. This phenomenon can explain the difference among experimental data reported by different studies and the difficulty in improving the reliability of the correlations for metastable flow.

The neglect of metastable flow in HEM will lead to lower refrigerant mass-flow rate predicted by the theoretical analysis. But many studies[35,48,51−54,68−71] show that the deviation of HEM from experimental data is within ±15%, which may satisfy the requirements in engineering applications.

The actual slip ratio between vapour phase and liquid phase is less than 2, as shown by Lin's experiments[32]. The slip ratio in HEM is taken as unit, and is not far from the actual value. Separated phase model can predict the refrigerant parameters along the tube more accurately, but the predicted mass-flow rate is similar to that by HEM[50,71].

The refrigerant in a refrigeration system always contains some lubricant oil. Oil can decrease the cross-sectional flow area, thus decreasing refrigerant mass-flow rate. But the lubricant can decrease the refrigerant flow friction, thus increasing mass-flow rate[72] on the other hand.

(4) Empirical correlation model

Distributed parameter model is reliable but complicated. The most important advantage of empirical correlation model to distributed parameter model is that it is simple in its functional form and easy to calculate. But an empirical correlation model of capillary tube is usually suitable only for a limited range of working conditions. If a new refrigerant is used, or working conditions and configuration parameters change a lot, then the coefficients in the empirical correlation should be renewed.

The available empirical models are mainly for adiabatic capillaries because this kind of capillary tubes is widely used and their empirical correlation models are easy to be developed due to fewer effective factors. The available empirical models can be classified into dimension associated model and non-dimension associated model. The dimension associate models[46,73]I are easy to be built up but they lack theoretical support and have limited application range. Non-dimension associated model was first presented by Bittle *et al.*[55], and later verified and improved by some other researchers[44,47,56,57].

The data base to determine the empirical correlation model is a set of experimental data[44,55,56,73], or calculated results by the distributed parameter models[46,47,57]. The advantage of the models based on experimental data is that the predicted results can be verified directly. But the available number and range of the experimental data are limited and the experimental data by different researchers are not always consistent, so the accuracy of the models based on experimental data cannot be widely recognized. The advantages of the models based on calculated results are that the range of interested values can be selected arbitrarily, and the consistentness among predicted values can be easily verified. But the predicted results by this kind of model need further verification by experiment data. Considering the maturity of the distributed parameter model, we recommend the models based on predicted results because it can avoid uncertainties in experiments and retain higher efficiency in modeling.

(5) Approximate analytic model

Distributed parameter models are complicated, while empirical correlation models have some drawbacks in its generalization. Yilmaz[74] presented an approximate analytic model, which is suitable for refrigeration system simulation. The complexity and accuracy of this kind of model are in between the distributed parameter model and the empirical correlation model. In this model, the adiabatic flow in the capillary is simplified into an isenthalpic flow first, and then the correlation between pressure and specific volume of two-phase refrigerant under isenthalpic condition is developed in order to solve the momentum equation by integration. Our recent studies in Shanghai Jiaotong University have improved the approximate analytic model. The application range of this model has been extended and the accuracy has been improved[75−77].

(6) Serial and parallel characteristics of capillary tubes

Most studies on capillary tubes focus on single capillary tube. But multi-capillaries are often used in actual appliances. For example, several parallel capillary tubes are often used in a single air conditioner, and serial capillary tubes are used in some air conditioners operating under heat pump mode. So the modeling of multi-capillary tubes should be developed based on those for single capillary tubes. Such studies are also in progress by our group in Shanghai Jiaotong University[78,79].

### *1.3 Evaporator and condenser model*

Evaporator and condenser are considered as heat exchangers, and the following models are available to simulate the functions both for evaporator and condenser.

(1) Steady state model

The steady state models for heat exchangers are mainly used to describe the steady state characteristics of heat exchangers, and can be divided into 3 types.

1) Single-node model or lumped parameter model. The logarithmic mean temperature difference method, which is widely used to predict steady state performance of heat exchangers without refrigerant phase changes, is a typical lumped parameter model[80]. For the heat exchangers that have phase change process, the logarithmic mean temperature difference method is ineffective, and the accuracy of lumped parameter model becomes quite limited.

2) Multi-node model or distributed parameter model[81−83]. This model divides the heat exchanger into several control volumes and parameters in each control volume are lumped. Another way to set up this kind of model is to discrete the partial differential equations directly. This kind of model has higher accuracy than lumped parameter model, but the simulation time becomes longer.

3) Zone model[84,85]. Condenser is normally divided into 3 zones: superheated zone, two-phase zone and subcooled zone, and lumped parameter models are developed for each zone. Evaporator model normally includes the lumped parameter model for two-phase zone and that for superheated zone. Both the accuracy and the calculation speed of zone model are in between those of the lumped parameter model and distributed parameter model. There are little difference between the zone model and distributed model, while the calculation speed of zone model is obviously faster than that of the distributed model[84], so the zone model is a suitable model for system simulation when the requirement on accuracy is not extremely high.

(2) Dynamic model

Dynamic models for heat exchangers can be categorized into following two models:

1) Transient model. This model is mainly used to represent the heat exchanger dynamic response to the variation of the boundary conditions during the operating process. It is often applied to controlling the state parameters such as superheat[86−93] or developing controllers[94]. In the transient response process of heat exchanger, the variations of some parameters are very small, so some nonlinear terms in the model can be linearized to make the model more simple or explicit.

2) Long-term dynamic model. This model is mainly used to describe the dynamic performance of heat exchangers in simulating the start-up or shut-down process of refrigeration system[95]. The variation in parameters of heat exchangers in the start-up or shut-down process is so large that almost all of the nonlinear terms in the model should be maintained, resulting in more

difficulties in the calculation.

According to the parameter lumped characteristics, dynamic models can be classified into 3 models: single-node model[4−12], multi-node model[96−100] and zone model l[94,95]. But we will not address them here because of limited space.

## 2 Models for envelop structure

Some refrigeration systems such as chillers do not have envelop structures, and we need no envelop-structure model in the evaluation of the performance of such appliances. But there are a lot of refrigeration appliances, such as household refrigerators and cold storages, consisting of envelop structures. Some characteristics of these appliances, such as the cooling-down speed and temperature recovery time of household refrigerator, have close relation to the dynamic performance of the envelop structures, so dynamic model for the envelop structure is necessary.

An envelop structure is often made of solid materials, whose property variation can be ignored in the actual range of refrigeration conditions. The envelop structure can be exclusively considered as thermal resistant in the steady state simulation of the refrigeration appliances, and it is easy to calculate. But the prediction of the dynamic characteristics of the envelop structure is more complicated.

In the earlier stage of development in dynamic simulation of refrigeration system, only transient characteristics were studied[4,5]. In those cases, the ambient conditions related to the envelop structure were assumed to be unchanged because the period time of the transient process is much shorter than the time constant of the envelop structure. But this assumption is not fit for a long-term process simulation.

It is a reasonable challenge but not the best method to formulate the heat transfer differential equations and solve them together with the equations for other components during the entire simulation process. The reason is discussed below.

The envelop structure should be divided into a lot of layers, and many corresponding dynamic equations for these layers have to be formulated. They should be solved in each time interval in order to predict the dynamic performance of the envelop structure with high accuracy. But the solving processes for these equations may take a long time and decrease the simulation stability. But the calculated accuracies of envelop structure model and also of the refrigeration system model will decrease if less layers are used for the envelop structure. From the viewpoint of system dynamic simulation and optimization, the calculation time required by the envelop structure model should be as short as possible, and it is better not to combine the major parts of the computing tasks of the envelop structure into the system simulation.

Therefore it is not recommended to use direct differential method to solve the envelop structure model in the dynamic simulation for refrigeration system.

### *2.1 Dynamic model for envelop structure based on classical control theory*

The envelop structure can be dealt with as a linear system because its properties change little. We can first calculate the transfer behavior of the envelop structure, and then synthesize them with the disturbance variables to calculate the system dynamic response in the simulation of refrigeration system. As there is only one time to solve the differential equations for envelop structure, the calculation time is not very long. Such a method is very suitable for dynamic simulation of refrigeration appliances. This kind of methods include response coefficient method (corresponding to S transfer function), transfer coefficient method (corresponding to Z transfer function) and harmonic wave method (corresponding to sinusoidal transfer function)[101−109].

When the harmonic wave method is applied to structural walls, the decay and delay to each stage harmonic wave can be calculated in advance. The response can easily be obtained after the synthesis of each stage harmonic wave is inputted. The concept of unstable heat transfer through a plane plate introduced by harmonic wave method, such as decay, delay and heat accumulation characteristics, has obvious physical meaning and is familiar to us. The harmonic wave method has the premise of periodic disturbance, which is inconvenient for refrigeration appliance simulation. The response coefficient method appearing at the end of the 1960s cast off the limitation of the periodic disturbance premise, and can be used more easily. There are many coefficients to be memorized in response coefficient method, while a very few coefficients are needed in the Z transfer coefficient method. But the calculation method for Z transfer coefficients is more complicated than that for response coefficients. In order to simulate the dynamic characteristics of refrigeration appliances quickly, the Z transfer coefficient method is recommended.

### 2.2 Dynamic model for envelop structure based on modern control theory

The response coefficient method and the Z transfer coefficient method were based on classical control theory when they were initially proposed. The state-space method in modern control theory can also be used for envelop structure model[110], which has the following characteristics:

1) Formula deduction is simple. Formula deduction with Laplace transformation based on classic control theory should convert the time-domain problems into frequency-domain problems and then reconvert them back to the time domain. Theses two times of conversions are complicated. But all the problems are solved only in the time domain with the state-space method, so the process is simple enough and well understandable.

2) The calculation on computer is easy to realize. Programming to calculate differential coefficients, pole point or root of complex function, required by the Laplace transformation method, is quite complex. But programming is simple for the calculation based on the state-space method because only operations of some matrix are needed.

3) The time-dependent temperature and heat flow variation inside the plate can be represented conveniently. S transfer function belongs to outside model, and only the time-dependent output temperature and heat flux variation can be obtained. But the state-space method is an inside model, and can easily reproduce the time-dependent variation of temperature and heat flux at each state point.

4) There also exist some drawbacks in the state-space method. For example, the state-space method is actually a semi-differential method, and its accuracy is lower than the Laplace transformation method. But case studies show that its accuracy can satisfy the requirements in engineering applications[1].

### 2.3 Synthesis of transfer function and variable time interval

The temperature variation in a refrigeration appliance with envelop structure depends on the characteristics of the entire envelop, which may consist of a lot of plane walls. But the characteristics of different plane walls may differs significantly, so we should set up a model for the entire envelop on the basis of the model for each plane wall. The methods for establishing the model for the entire envelop among those for each plane wall include: 1) common ratio method[111], 2) dominating characteristic root method which is very stable in getting low orders of transfer function[112,113], and 3) system identification method[114].

The time interval of the envelop structure algorithm based on transfer function is fixed. But the time interval of the refrigeration system simulation may be changeable, so it does not match that of envelop structure. As the calculation time of refrigeration system model is longer than that of the envelop model, we should change the time interval of the envelop model so that the time intervals of the refrigeration system and of the envelop structure are equal. The variable time-interval algorithm for envelop structure can be classified into the following three types:

1) Interpolation method[1]. This method is simple. The calculated results by this method are general satisfactory when the disturbance changes slowly. But for the envelop structures affected by fast variation disturbance, this will lead to large error in calculation.

2) Variable time-interval algorithm based on the different time-interval relationship between the response coefficients/transfer function coefficients. With this method, we should first establish the conversion equation for different time-interval (long interval is the integer times of the short interval) response coefficients/transfer function coefficients, and then develop the variable time-interval algorithm by using the superposition theorem in the linear system[115,116].

3) Define new response coefficients from the viewpoint of disturbance decomposition, and then create a new self-adaptive variable time-interval response coefficients, such as variable time interval algorithm based on the cross response coefficient[117].

## 3 Fast calculation method for refrigerant thermal properties

### 3.1 Requirements on calculation method for refrigerant thermodynamic properties in system simulation

There are numerous calculations of refrigerant thermal properties in the simulation of refrigeration and air conditioning appliances, so the calculation model for refrigerant thermodynamic properties play a vital role in the simulation of refrigeration and air conditioning systems. Furthermore, the effect of the refrigerant thermal property model also influences the component model selection in the entire system simulation. If the calculation of refrigerant thermodynamic properties is too complicated, the models for the components have to be simplified in order to guarantee the calculation speed of the entire system simulation, which will influence the function and accuracy of the system simulation. Thus, the following aspects in the calculation of refrigerant thermodynamic properties should be considered from the viewpoint of system simulation:

1) Fast speed. Since there are numerous calculations to be called on refrigerant thermodynamic properties in the simulation, the calculation speed of refrigerant thermodynamic properties is a vital factor for practical simulation.

2) High stability. Since there exist numerous times of calls for the calculation of refrigerant thermodynamic properties, calculation divergence is likely to happen even if divergence probability is low in a single calculation, and the requirement on the stability is extremely important.

3) Reversibility. In the simulation of refrigeration and air conditioning appliances, many refrigerant thermodynamic properties need to be converted to each other. Even a very little deviation occurring in a single conversion process will lead to a large difference in the final calculated results because of a large number of iterations required.

4) Continuity and smooth. Only an iteration of continuous functions can provide a convergence result. As some differential coefficients are used for some kinds of refrigerant thermodynamic properties, the differential coefficients of those thermodynamic properties should be continuous too, i.e. the function of the refrigerant thermodynamic properties should be smooth.

The EOS (equation of state) method is usually used to predict refrigerant thermodynamic properties in a wide range with a high accuracy. But the calculation speed and stability are limited by unavoidable iterations in calculation.

### *3.2 Fast calculation method for refrigerant thermodynamic properties*

Since the EOS method has limited calculation speed, fast calculation methods are desirable.

Look-up table method is an easy way to improve the calculation speed of refrigerant thermodynamic properties. Before using this method a table that contains the values of different refrigerant thermodynamic properties should be established in advance. These values are mostly calculated with EOS. The simulation program will look up this table during the simulation process. If the state point is not included in this table, its property value will be calculated from those at its neighboring state points in the table with a linear interpolation method. This method is applied in the heat exchanger simulation software developed by NIST[118]. There is no need of solving the state equations, and this method can satisfy the high speed and stability requirements for simulation. But this method cannot guarantee the smooth requirement of simulation. In the look-up table, the refrigerant thermodynamic properties are given at many grid points. The refrigerant thermodynamic properties are linear in each mesh, but the refrigerant thermodynamic properties at the intersection grid points of different meshes are continuous but not smooth. This will limit the use of differential coefficients during the simulation.

Explicit polynomial regression method is another simple yet fast calculation method for refrigerant thermodynamic properties. Explicit high power polynomial functions, regressed for thermodynamic properties, have higher calculation speed and better stability than EOS while the accuracy is still satisfied[119,120]. But the big shortcoming of this method is that it cannot guarantee the calculation reversibility. So divergence might happen unless extremely high regressing accuracy is applied.

Cleland[121,122] presented a method to speed up the calculation of refrigerant thermodynamic properties and gave the correlations for R12, R22, R114, R502, R717(NH3) and R134a. The formulae for saturation pressure and temperature are similar to the Antoine equation, and the calculation reversibility can be ensured. The function for saturated liquid and vapor enthalpy is regressed into a cubic polynomial equation, and the superheated enthalpy is regressed to functions of saturation temperature and mass quality. This model is simple, practical and consumes less calculation time. Its effective range is of application covers –60℃－60℃ in subcritical region, but does not cover the region near the critical point. It cannot be used for zeotropic refrigerant mixtures.

### *3.3 Implicit regression and explicit calculation method*

The refrigerant thermodynamic properties are given as a monotonic function in the range in common use which is heuristic for us to apply the reversible function for regress. The highest power of the polynomial in this equation is not larger than 4 in order to solve it analytically. But lower power polynomials often provide lower accuracy. This can be explained by using the theorem of formula expansion. A polynomial can be considered as the remaining low order parts of the expanded form of EOS. The calculation accuracy of the polynomial is lower than the EOS because only low order parts of the expanded form of EOS are included in the polynomial. The more lower-order items the polynomial includes, the higher accuracy it exhibits. The number of the lower order items should be increased in order to improve the accuracy of the polynomial. The number of lower order items in the expanded form of an explicit formula can be increased if the number of independent variables is increased. We can convert the explicit formula into an implicit one, and the original dependent variable is changed into an independent variable for the purpose of increasing independent variables. After the regression process, explicit formulae can be obtained by solving the regressed equations.

As a practical application of the above method, our resent study at Shanghai Jiaotong University proposed an implicit polynomic model for explaining refrigerant thermodynamic properties[123]. This model is not only suitable for both pure refrigerants and refrigerant mixtures. In order to extend the applicable range of fast calculation, the piecewise smooth regression method can be used. That is to divide a wide range into several subsections and to guarantee the continuity of the function and its differential coefficient at the intersection point. The deviations of the fast calculation result by this kind of implicit model from the original property values can be ignored while the calculation speed can be increased by about 1000 times. The stability of this model is guaranteed because no iteration is needed. This model can also guarantee the calculation reversibility since the relevant variables are analytical solutions of the same implicit equation. At present, this implicit model is the best model for calculating refrigerant thermodynamical properties during simulation of refrigeration and air conditioning systems.

## 4 System model and algorithm

In order to combine the component models into an overall model for refrigeration systems, the relationship among parameters of each component should be clearly known. There are many parameters affecting the refrigeration system, and most of them interact with each other. So some basic and necessary parameters in each component must be selected as a representative of this model.

Parameters in the refrigeration system include the self-influencing parameters and inter-influencing parameters. Self-influencing parameters only influence the system performance for a single component. Inter-influencing parameters influence the performances of other components and the entire appliance. The role of the self-influence parameters is well reflected in the component models, but the interaction of the inter-influence parameters should be quantitatively studied in the system simulation.

There are two kinds of approaches to analyzing the inter-influence parameter: 1) using the relationship between the different components produced by the refrigerant mass flow; 2) using the relationship between the different components produced by heat transfer. There are larger differences between the two approaches, and they should be studied independently[1,3].

Fig. 1 shows the schematic of a refrigeration appliance having an envelope structure. The refrigeration system and the envelope structure interact with each other by heat transfer. After further dividing the refrigeration system into the components of evaporator, condenser, compressor, etc, and defining the coupling relation among these parameters, these component models can be combined into a system model.

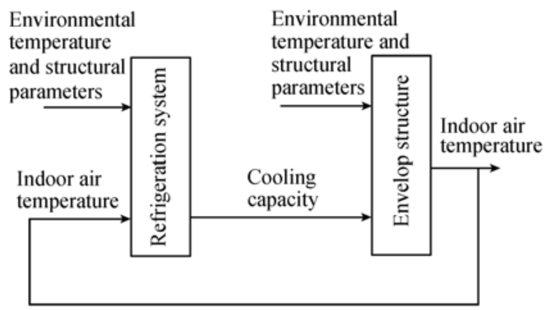


Fig. 1. Schematic of the refrigeration appliance having envelop structure.

The algorithm for system model is more complicated than that for a single component model because not only each component model but also the coupling relationship should be determined in solving the system model.

Two kinds of algorithms for the refrigeration and air-conditioning appliances are available in literatures.

One is the simultaneous solving method. This method combines all the equations and initial conditions into an equation group and solves these equations simultaneously with Euler method[5], Newton-Rahpson method[124], Runge-Kutta method, etc. Simultaneous solving method has wide uses, but it has no physical meaning in calculation process. It is also difficult for the user to detect the cause if divergence happens in the calculation and the calculation stability is not easy to be ensured.

The other algorithm is the sequential module method[125,126]. This method uses certain kinds of balance conditions, such as the mass balance, as the convergence criterion. A set of initial values is assumed, and then calculation starts from the innermost cycle, and other parameters are outputted. If the convergence criterion is not satisfied, the old assumed initial values would be updated and then we have to repeat the iteration again. The cycles in all levels are calculated in such steps. The advantages of this method are that it has obvious physical meaning, and it is easy to debug and to ensure the calculation stability. Its shortcoming is that it has low generalization and the algorithm should be designed according to the actual system cycle steps.

When simulation is done by non-professional experts in the field of refrigeration and air conditioning, the sequential module method is recommended because it is easier than simultaneous solving method.

It is better to study the relationship between the complexity and accuracy of the model before simulation, and a simpler model guaranteeing certain accuracy is preferred because it is easy to be solved[127].

## 5 Model-based intelligent simulation methodology

The intelligent simulation methodology of refrigeration and air conditioning appliances resort to the method of combining the modern artificial intelligence technique with mathematical model of refrigeration and air conditioning appliances, so that the simulation software have a certain “intelligence ” for simulating the actual complex objectives. This technology can help the user to cope with the technical problems in simulating complex objectives, and make the simulation software more practical.

The artificial intelligence technique was used to predict the performance of refrigeration and air conditioning appliances as a simple method[21,22,128,129]. Pure artificial intelligence techniques, such as ANN (artificial neural network), fuzzy theory and expert system belong to non-model method, and they do not need mathematical models but have high adaptability. In using such a method we still encounter some unsolvable problems brought by the imperfection of the artificial intelligence technique itself and the limitation of the user’s understanding of it.

The classical mathematical model method has been theoretically studied and practically applied for the latest many years. The mathematical model is more likely to ensure the qualitative correctness of simulation than an intelligent method. It is a good way to combine the classical mathematical method and the intelligent method together in order to take the advantages and to avoid the shortages of both methods[2]. For example, the predicted result of the classical mathematical model can well fit the experimental data if its empirical coefficients can be adopted by an artificial intelligence module. The training task of the artificial intelligence module will reduce, and the training speed can be accelerated if the calculated results by the theoretical model are used as the initial or prior assumed values for the artificial intelligence module. The adjustment process of the empirical coefficients in the mathematical model can be converted into the training process of the artificial intelligence module, and can be executed by the computer itself. In this way, less or even no artificial adjustment is needed in the simulation, and self-learning, self-adjusting and self-adapting function can be realized. On the other hand, the number of input parameters and the dimension of the artificial intelligence module will be decreased since many important parameters including configuration parameters are already included in the mathematical model. Those complicated, empirical and even uncertain factors in the theoretical model can be incorporated into the artificial intelligence module to simplify the mathematical model.

For the heat exchanger model, ANN can be used to make up the deviations between the original model prediction and experimental data. Distributed parameter models are usually used for highly accurate simulation of heat exchangers. But the simulation speed of a distributed parameter model is slow. In order to raise the simulation speed with good accuracy, we can use the lumped parameter model first, and then use an ANN to make up the difference between the lumped parameter model and the distributed parameter model[2,130].

For compressor, we can combine a simple mathematical model containing two empirical parameters of mass flow coefficient and motor efficiency with an intelligent module, and the combined model may provide us very high accuracy. These two empirical parameters, which are usually regressed by experimental data, are calculated by the intelligent module. The artificial intelligence module can be either the ANN[131] or fuzzy algorithm[24].

For capillary tube model, the original nonlinear equations can be converted into some integral equations by using the ANN to identify some coefficients. The simulation can also be sped up by using this method[132,133].

In using the ANN to improve the performance of the entire refrigeration system, we should first determine the characteristic parameters indicating the important performance of the system. These characteristic parameters may include input power to compressor, condensing pressure, evaporating pressure, condensing heat, cooling capacity, the refrigerant pressure drop in the evaporator, etc. The simulation result of the characteristic parameters can be improved by adjusting the empirical parameters in the refrigeration system model, such as the compressor volumetric efficiency, motor efficiency, heat transfer coefficients, friction coefficient, etc. These empirical parameters are named quantitative parameters, which will directly influence the quantitative accuracy of the simulation program. The quantitative parameters have already been adjusted in the component models. But after all the component models are assembled into a system model, the quantitative parameters still have be adjusted because the characteristics of the components may change in the system.

The process of identifying and adjusting the quantitative parameters is very complicated. Adjustment of one quantitative parameter will lead to a variation of calculated results for the entire appliance, so these parameters can hardly be adjusted step by step by the user. A good way is to convert all quantitative parameters into a vector and then to optimize this vector in the entire system characteristic space. Considering the complexity of this process, the ANN is recommended when the adjusting process. Both direct adjusting method and deviation-based adjusting method are available[134].

## 6 Graph theory applications in simulation

We should developing general and reliable simulation algorithm in order to apply simulation technology widely in engineering. But it is difficult to accomplish this goal because there are a vast variety of refrigeration systems and its components.

CYCLE-11 developed by Domanski and McLinden[135], Cycle-Tempo developed by Verschoor and Van Gerwen[136] are only effective for simple theoretical cycle analysis and are still not applicable to practical appliances. There are some system simulations based on CFD software. For example, TRANSYS is used to predict the dynamic performance of supermarket refrigerators by Ge *et al*.[137] and Fluent to predict the dynamic performance of household refrigerators by Sorensen *et al*.[138]. But these kinds of CFD software are not designed specifically for refrigeration system simulation, and the calculation time is very long and calculation stability can not be ensured.

Graph theory can be applied to develop a general simulation method. Graph theory is an important branch of the algorithm theory, and abstracts a specific problem into a graph of nodes and verges. It has been applied to many fields, such as electric circuit network, fluid network, etc. In the refrigeration theory, refrigeration cycle is a baseline of various actual refrigeration systems, and it is usually described by lg $p$-$h$ diagram which is one kind of graph but needs further regulation based on graph theory. A heat exchanger can also be considered as a kind of fluid network with the confines on configuration parameters. Suitable general algorithm for heat exchanger can be developed with the help of ideas from the application of the graph theory in fluid network.

The following problems should be overcome when applying the graph theory to the refrigeration system simulation:

(1) How to convert the problem of solving refrigeration and heat exchanger models into a graph theory problem. The uniqueness and reversibility of the conversion are the keys in this process due to numerous information, such as flow direction and process type, is included in the converting process.

(2) How to optimize (or compress) the simulation algorithm. The generated simulation algorithm is not unique due to the diversity of the graph path. Low-efficiency simulation algorithm will lead to huge calculation quantity. Thus, optimizing (or compressing) the simulation algorithm is necessary to improve the application efficiency.

### *6.1 Construction of graph-theory-based steady-state simulation algorithm for refrigeration system*

Different refrigeration systems have different cycles. Rasmussem and Jakobsen[139] presented the cycle-based simulation idea. And the system simulation algorithm corresponds to the cycle graph.

*p-h* (or *T-s*) diagram is often used to represent the refrigeration cycle. But the refrigerant-flow direction must be added to the diagram in order to reflect the refrigeration cycle definitely. Using figures to stand for the process between every two state points, the entire refrigeration cycle will become a directed graph composed by multi nodes. Fig. 2 shows a directed graph for a two-stage compression refrigeration cycle.

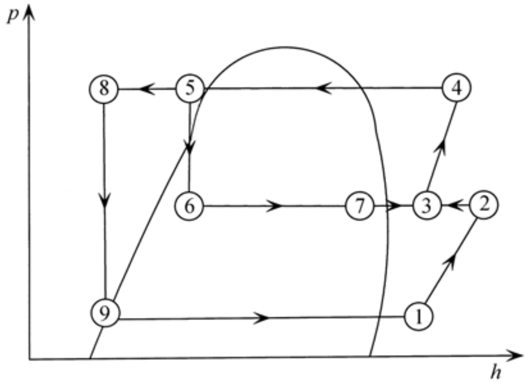


Fig. 2. Directed graph for two-stage compression refrigeration cycle.

The cycle in Fig. 2 can be expressed by the following matrix in eq. (1), where the information in rows refers to the process leaving the connection point, and the information in columns refers to the process getting to the connection point. If there is no connection in two points, then the figure in the position is 0. The figure 1 in row 1 and column 2 means that there is refrigerant flowing from point 1 to 2, and the process type is 1. The figure 4 in row 1 and column 9 means that there is refrigerant flowing from point 9 to 1, and the process type is 4. The meaning of each process-type figure is: 1, compression; 2, condensing; 3, throttling; 4, evaporating; 5, subcooling; 6, superheating; 7, liquid separating; 8, vapor separating; 9, mixing.

$$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 6 & 0 & 0 \\ 0 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 \\ 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

A general expression of the refrigeration system can be obtained with the above method based on graph theory[140].

### 6.2 *Graph-theory-based heat exchanger simulation methodology*

A refrigeration system may consist of a lot of heat exchangers with different configurations. A practical way to describe such a kind of system is to number each tube and the refrigerant flow direction within each tube.

The number of heat exchangers can be assigned according to the refrigerant flow sequence through each heat exchanger or according to its relative position in the network. After numbering heat exchangers, the tubes in each heat exchanger should be numbered. The number designation for the tubes starts from the lowest column of the front face row of the No. 1 heat exchanger (HX-1), and then the tubes are denoted one by one from bottom to top by #1, #2, … till the last row of this heat exchanger. The numbering of the tubes in No. 2 to No. *n* heat exchangers is the same as that for the No.1 heat exchanger, but the number should be increased one by one based on the largest number of the former one.

There are two kinds of position arrangement of heat exchangers. One is a parallel arrangement. The inlet air parameters do not affect each other in this case. The other is an overlap arrangement. In this case, inlet air parameters of the front row(s) will influence those of the rear row, and the outlet air-side parameters of the front row are used as the inlet parameters to the rear row.

In order to correctly describe the refrigerant circuits and the relationships among heat exchangers in the refrigeration system, directed graph and adjacent matrix in graph theory are applied. This kind of method has already been used in heat exchanger simulation[25] and optimization[141].

## 7 Trend of simulation technology development

The improvement of computer hardware, the progress of the fundamental simulation technique, and especially the increasing demand in the refrigeration industry have accelerated the application of computer simulation technique to the refrigeration and air conditioning field. In order to meet the needs in future, the refrigeration simulation technique should be further encouraged at least in the following two aspects.

1) Technologies to assist engineers to feel easy in developing or operating simulation software. One of

such technologies is general refrigeration system simulation platform based on graph theory. Another technique is model-based intelligent simulation technique to let the software have self-adaptation function.

2) Simulation technique for new types of refrigeration systems or components. For example, micro refrigeration units are used recently, but the assumptions on the model for traditional units are not suitable to it and new models are needed. Nanofluids are used in refrigeration appliance and new models are also needed to represent the refrigeration system using nanofluids.

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