1994

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Tiedemann, T. and Kruse, H., "Simulation of the Transient Behavior of Household Refrigerators and Freezers" (1994). *International Refrigeration and Air Conditioning Conference.* Paper 247.
http://docs.lib.purdue.edu/iracc/247

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ABSTRACT

Due to their contribution to the ozone depletion and the anthropogenic greenhouse warming effect caused by the refrigerant as well as the foam blowing agent household refrigerators and freezers were attracting public attention especially in Western Europe. The conversion to the use of environmentally benign fluids as refrigerants and foam blowing agents requires a large number of extensive, expensive and time consuming performance tests. This number can be reduced significantly by the assistance of a simulation program.

A program to simulate the dynamic behavior of household refrigerators and freezers has been developed at the institute. The main object of this program is not to simulate a type of refrigerator very exactly but to calculate the effect of constructive modifications on a refrigerator with regard to energy consumption and compartment temperature. In order to develop a model, only the geometric data, the material properties and the performance graph of the compressor have to be known.

The thermodynamic basic principles as well as the application of the simulation model are shown for a simple refrigerator. Using the simulation program, the effect of various parameters on the cycling operation and the energy consumption is examined and a comparison with measured data is made.

Provided that the modifications of the specific refrigerator are not too far from the original one, an exact prediction of variations to the characteristics of the refrigerator can be expected.

INTRODUCTION

Unlike many other refrigeration plants, for the simulation of household refrigerators, the inclusion of the housing is, besides the calculation of the refrigerant circuit, very important. Through the large thermal inertia of the insulation used in the housing, compared to that of the refrigeration cycle, the transient behavior of the refrigeration cycle is mainly influenced by the housing.

Once a model of a refrigerator or freezer is developed parameter studies can be performed very easily with the program. These parameters can be :
- compressor type
- thickness, heat conductivity and material of insulation
- size and material of condenser and evaporator
- size of the compartments
- switching temperatures of control device

SIMULATION MODEL

Very fast transient changes in the refrigeration cycle occur only during cycling operation for a short period directly after the compressor has started to operate. The prevailing part of the cycling period can assumed as quasi-stationary. In the housing there are on the contrary changes in the temperature during the complete cycle of operation which have to be taken into account for the simulation. Even in the measurements, the behavior of the whole system of refrigeration cycle and housing is always determined. A separate development of each of these two parts may not influence the whole system to the same degree.

Basis of the Simulation Model

In continuation of a research project funded by the German Government [1], a method of elements is used for the simulation model. Therefore, the structure of which the temperature data has to be calculated, is divided into separate plain or volumetric elements. Inside each element all material properties as well as the temperature are considered to be constant. Different elements can be coupled thermally by heat conductivity, convection or radiation.

As an illustration, the heat transfer through a refrigerator wall (figure 1) may be considered. According to the selected model this wall is divided into three elements:

element 1: the ambient air with a constant temperature
element 2: the surface of the wall, including half of the outer sheet
element 3: covering the inner half of the sheet, the whole insulation and the outer half of the inner liner
element 4: the surface of the inner liner including half of the inner liner
element 5: the air inside the compartment.

In this example every type of heat transfer occurs: Between the elements 1 and 2 and 4 and 5 respectively there is a heat transfer caused by natural convection. From the element 2 to 3 and 3 to 4 there is a heat transfer by heat conduction. Furthermore, there is a heat exchange by radiation from element 4 to all other elements inside the compartment as well as from element 2 to the ambient environment.

The heat exchange between two elements by conduction can be calculated on the known thermal conductivity and the specific heat capacity of both materials by the known equations. In the used model the heat conduction is considered to be only one dimensional and perpendicular through the wall.

A heat exchange by radiation can be found only for elements on the surface, either the outer casing or the inner liner. The energy flow of radiation is calculated using simple relations as described i.e. in the VDI Wärmeatlas [2]. The third type of heat transfer, convection, also can only occur on surface elements. Depending on the specific kind of the heat transfer (vertical, horizontal with heat transfer from above to below or horizontal with heat transfer from below to above), a suitable equation from the VDI Wärmeatlas [2] is selected.

Exceptions are the elements representing the evaporator, the condenser and the compressor. Besides the heat exchange with other elements, a heat source is attached to them. The condenser and the compressor are considered to have a positive source, whereas the evaporator has a heat sink. The capacity of these sources is calculated in the simulation process of the refrigeration cycle.

With these types of heat transfer, the temperature of each element can be determined by a linear differential equation of first order. For a model of n elements a system of differential equations is set forth, which is solved using suitable mathematical routines (backward differention formula method). The solution represents the history of temperature for each element.

The refrigerant cycle is calculated as a simple cycle existing of compressor, condenser, capillary tube, evaporator and internal heat exchange between capillary tube and suction line. The temperatures of the elements representing the evaporator and the condenser are considered to be the evaporation and condensing temperature respectively for the further computation of the cycle. Using these values, the cooling capacity and the power input of the compressor can be determined using a performance graph measured under steady state conditions on a calorimeter. Due to the conditions of this declaration, the obtained data has to be converted to the specific actual conditions of the refrigerator. The required refrigerant properties are calculated using the Lee-Kessler-Plöcker [3] equation of state. Based on the modular structure of the program, the usage of other property routines as well as the introduction of simple polynomial equations, i.e. as suggested by Kruse and Küver [4], can easily be realized. The application of an equation of state offers the advantage of including various refrigerants and refrigerant mixtures in the simulation process at the expense of increasing computing time.

In order to realize the cycling operation in the simulation, the temperature of every element can be chosen as a control device where the upper and lower switching temperatures can be defined independently. If the temperature of the element which has been defined as the control device falls below the lower switching temperature, the compressor is 'switched off'. This means that the heat sources of the condenser, evaporator and compressor are defined to zero. Through the heat input into the housing, the temperatures of the elements are increasing until the temperature of the control device element reaches the upper switching temperature and the compressor is "switched on" again.

Having finished the simulation over the period of a complete cycle, the relative and absolute running time, the energy consumption and the average compartment temperatures according to standards can be determined. Also, the history of the temperature of every element, the refrigerant pressures or the power consumption over a defined period can be plotted or the heat input through a wall can be calculated.

Modeling

The main object in the development of the simulation program was to enable modeling when only geometric data, material properties and a performance graph of the compressor are known. An adaption to measured data, if required, should be possible by changing only very few values.

Figure 2 presents the model existing of 53 elements of a common European 162 l single temperature refrigerator. The evaporator (element 1) as well as the condenser (element 2) are foamed in the rear wall, the evaporator is covered with a polystyrole inner liner. Besides the evaporator, condenser, compressor and the housing, the air in the compartments and the ambient air represent elements.

The partition of the refrigerator into elements has to be done in that way that the assumption of a constant temperature over the element is accurate enough and the type of heat transfer to other elements can be defined clearly. For each element the dimensions (length, width, thickness), the mass and the material have to be defined for the program. Furthermore, the type of heat transfer to any other element must be defined for each element.

Additionally, the specific heat capacity and the heat conductivity of the used materials, the refrigerant and the type of compressor, the ambient temperature, the code number of the element acting as the control device and the switching temperatures have to be defined. The program uses the performance graph of the selected compressor and refrigerant or, if there is no measured data for the refrigerant or the mixture available, calculates these data from measurements of another refrigerant with the same compressor.

COMPARISON WITH EXPERIMENTS

Models for various refrigerators and freezers have been developed. The comparison of computed and experimental results is further made for the refrigerator introduced in section 2. The calculated and measured data of energy consumption and relative running time versus the average compartment temperature for this refrigerator is shown in figure 3. In general, the results of simulation are in accordance with the experimental data, only for permanent running and high ambient temperatures there is a deviation. Figure 4, in which the absolute running time is compared also proves the reliability of the simulation program. This correspondence of calculated and experimental data is an important precondition for the reliability of further calculations. It should be stressed here that the purpose of the simulation program is not to calculate a type of refrigerator very exactly, but to reliably predict the influence of constructive modifications to the transient behavior and energy consumption. Examples for this are presented in the following figures.

Figure 5 shows a comparison of measured and calculated data for the same type of refrigerator but with R11-reduced foam with increased heat conductivity. The effect of the changed heat conductivity of the foam is reproduced exactly. Another model of this refrigerator was equipped with a thicker insulation on the side walls of the cabinet and the doors. Furthermore, the compressor was changed to another type. Figure 6 proves again a good agreement of measurement and calculation.

All three modifications mentioned before (decreased heat conductivity of the foam, increased insulation thickness, changed compressor type) are realized in a third model. The comparison of experimental and computed data shows out minor deviations due to the modification of already three parameters.

These comparisons exemplarily prove the reliability of the simulation program to predict the effect of modifications at the refrigerator regarding energy consumption and compartment temperature.

Figure 8 shows the model developed for a freezer. The most important differences of this model compared to the all-refrigerator are the division into four compartments and the division of the evaporator into five parts successively passed by the refrigerant. As measurements of this freezer according to ISO-Standard require load inside the compartment, only very limited data without load is available. A comparison of experimental and calculated data is presented in figure 9. The deviations are larger compared to the all-refrigerator due to the air flow and the heat transfer between the partitions which are not taken into account for the simulation.

PROSPECTS

Further improvements of the simulation program require the inclusion of the air flow inside the compartment to represent the thermal stratification and the heat exchange between the partitions. To simulate also the loading as it is required for performance tests according to ISO-standards, a multi-dimensional model has to be introduced and the air flow between the load has to be considered. Both measures would cause a dramatic increase in computing time and thus reduce the applicability of this program.

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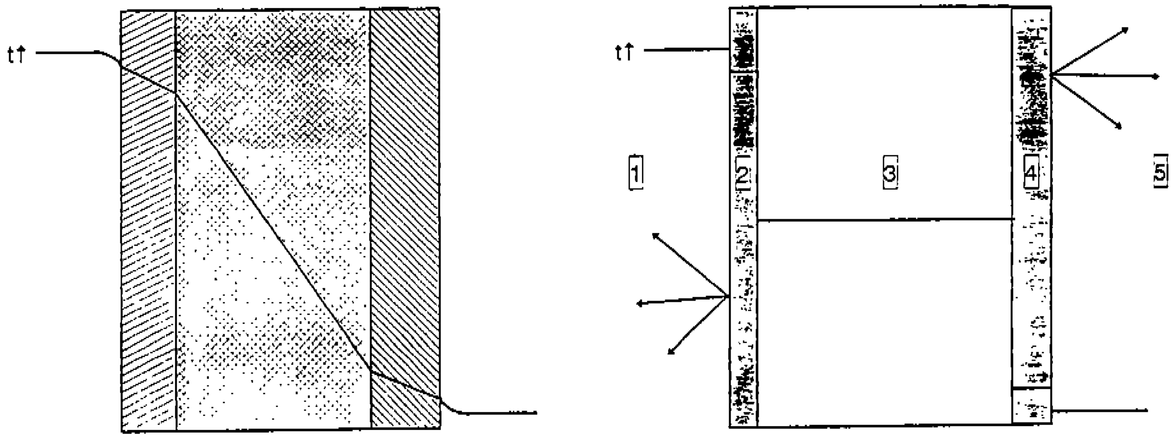

Fig. 1 : Elements of a refrigerator wall and heat transfer through the wall.

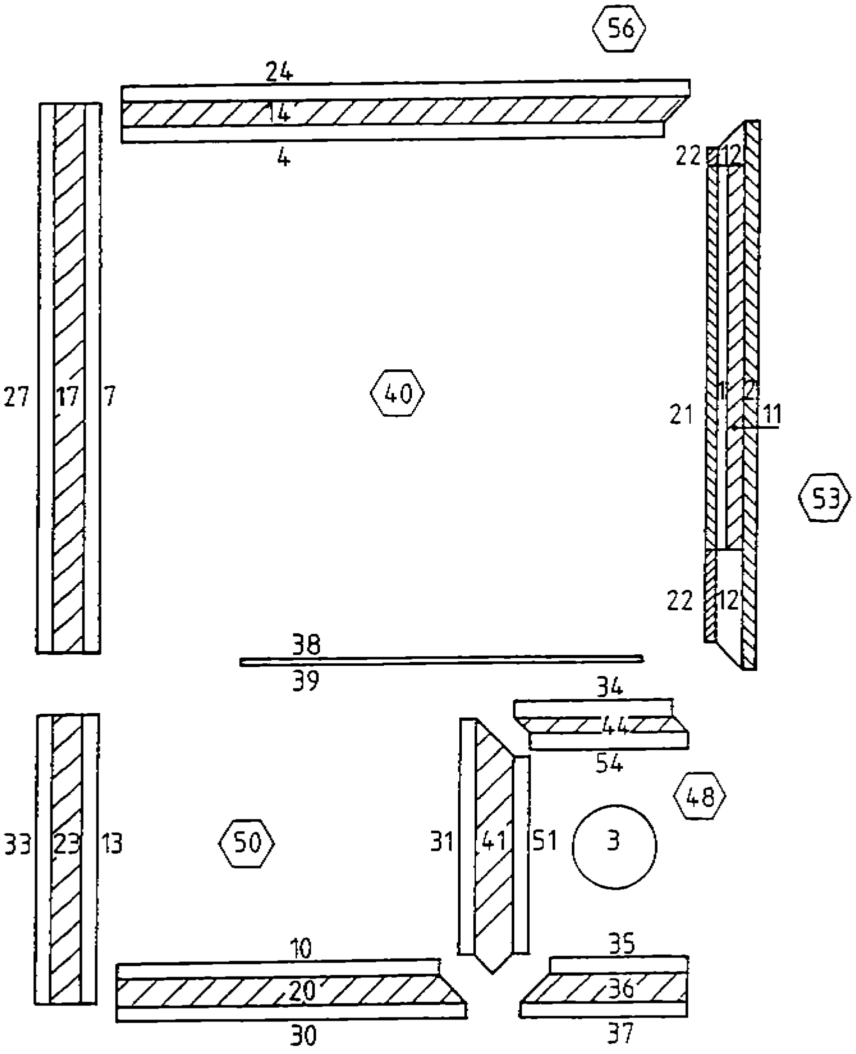

Fig. 2 : Model of a single-temperature refrigerator

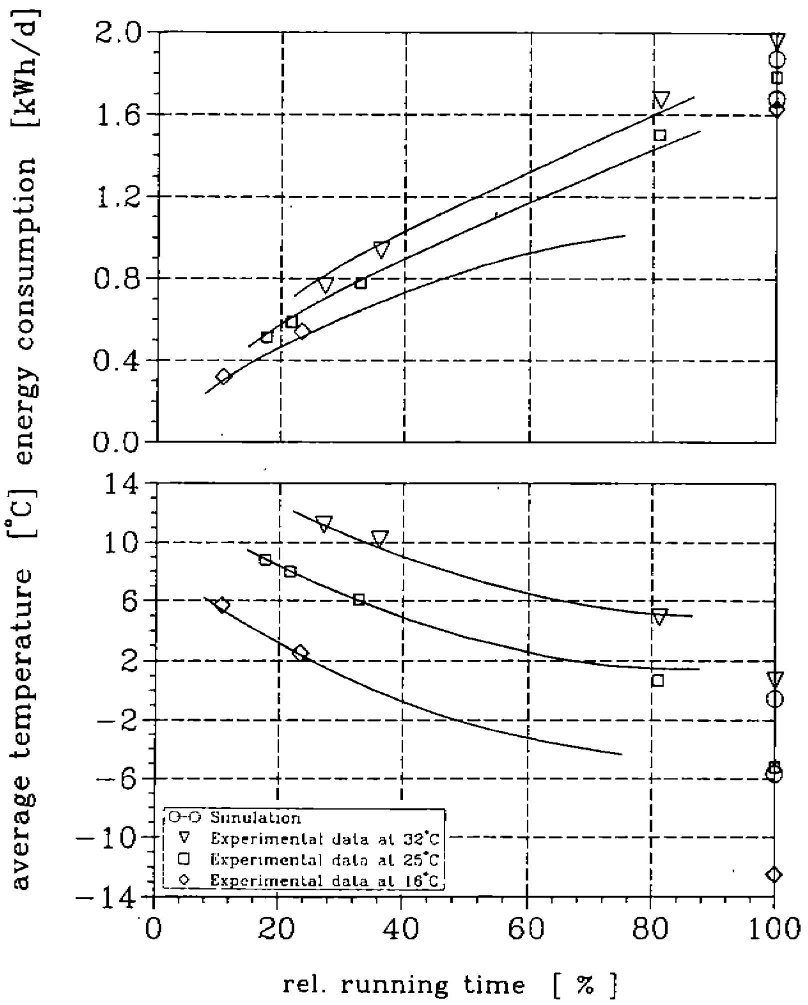

Fig. 3 : Comparison of experimental and calculated data for the single-temperature refrigerator

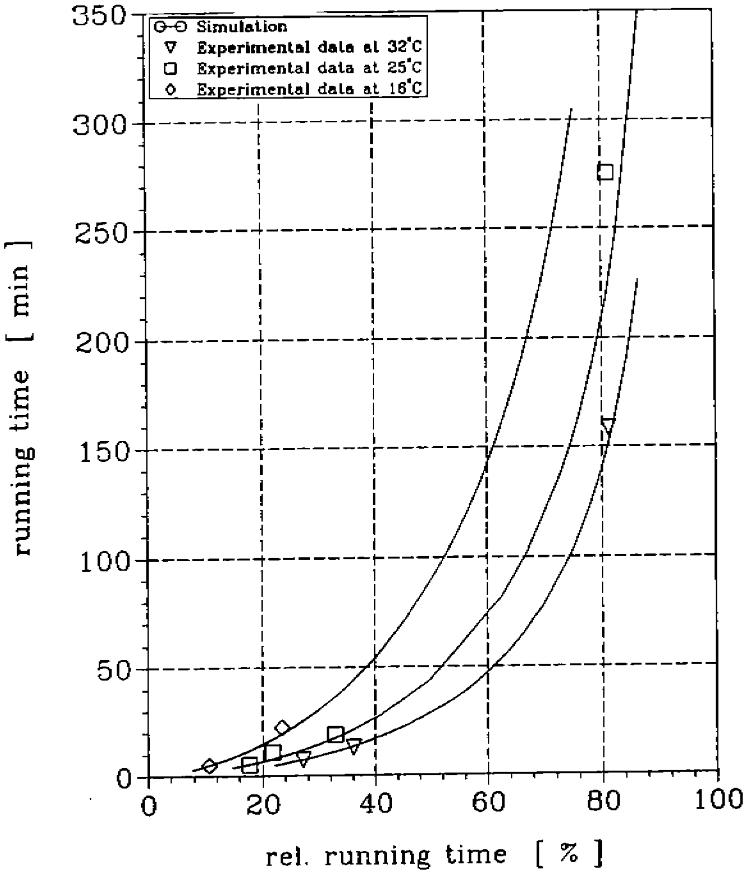

Fig. 4 : Comparison of experimental and calculated data for the single-temperature refrigerator

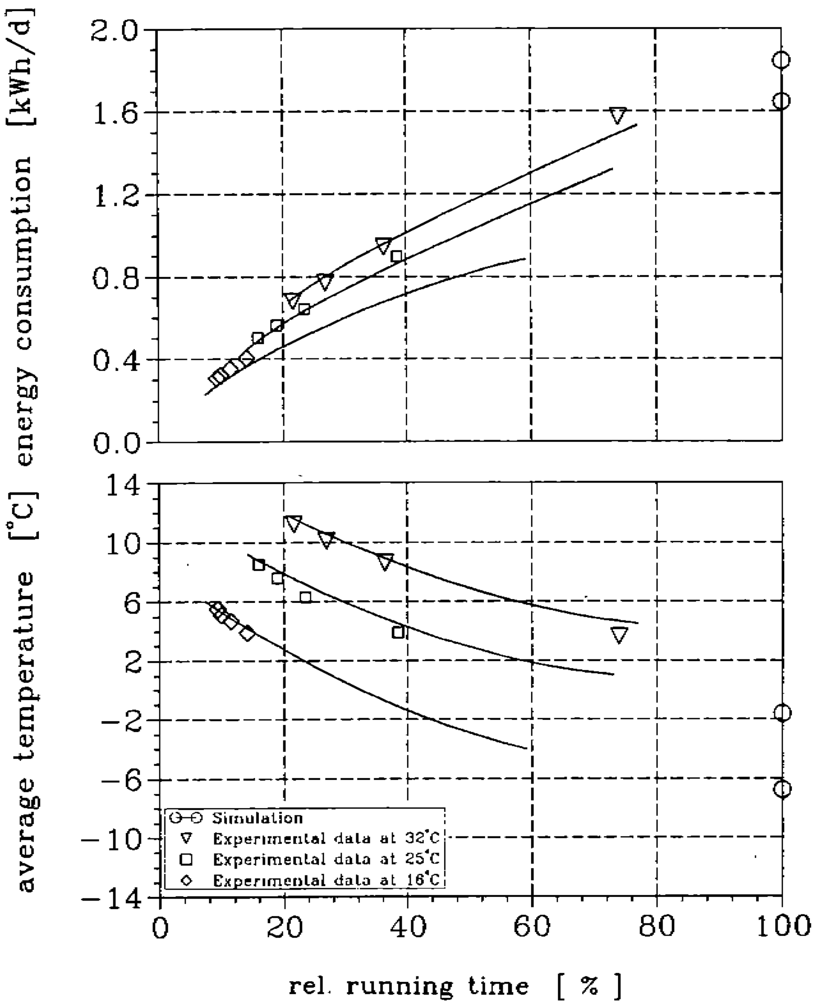

Fig. 5 : Comparison of experimental and calculated data for the single-temperature refrigerator with increased heat conductivity of the insulation.

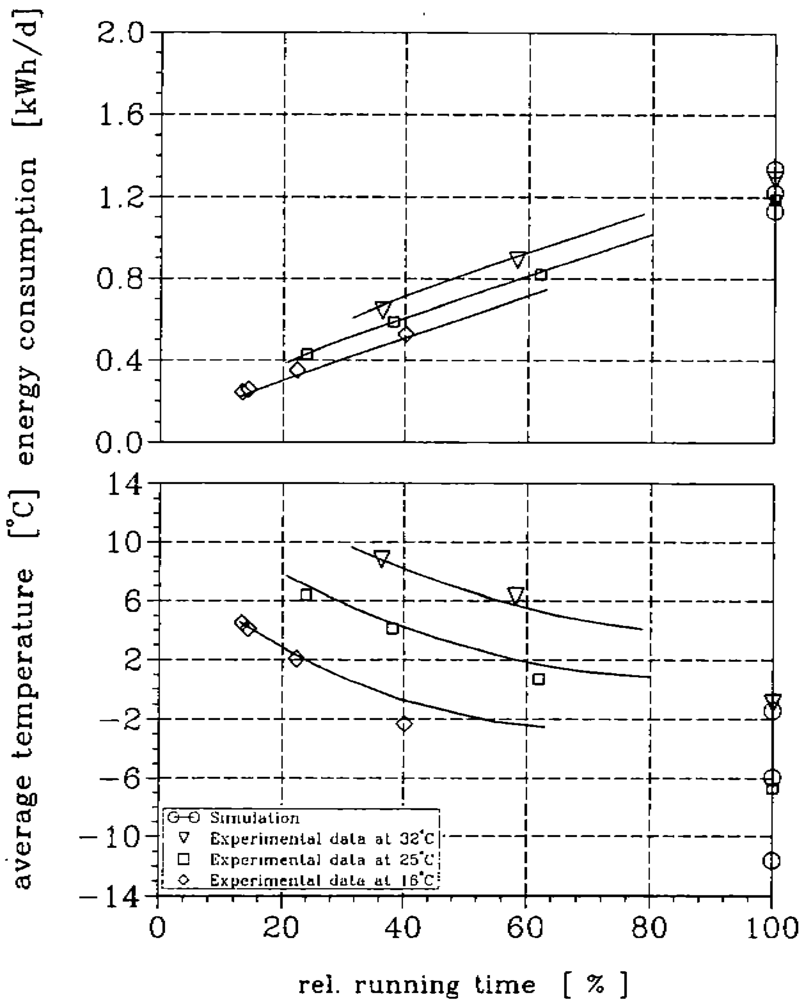

Fig. 6 : Comparison of experimental and calculated data for the single-temperature refrigerator with increased insulation thickness and another compressor type.

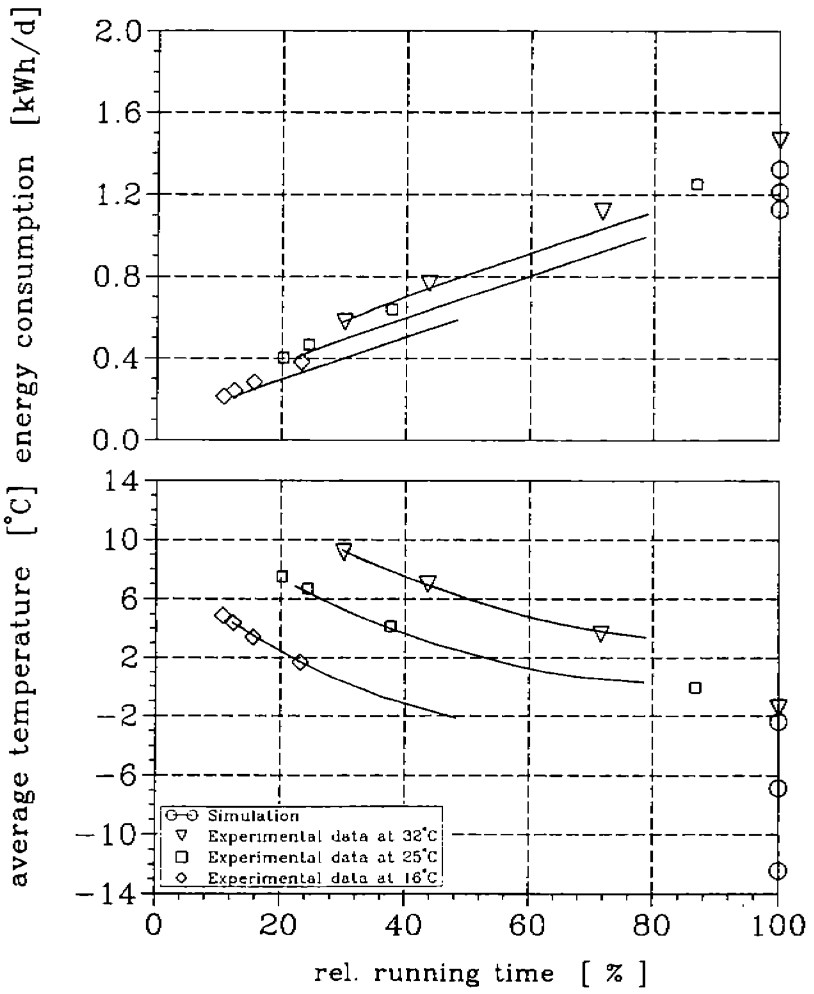

Fig. 7 : Comparison of experimental and calculated data for the single-temperature refrigerator with increased heat conductivity of the insulation, increased insulation thickness and another compressor type.

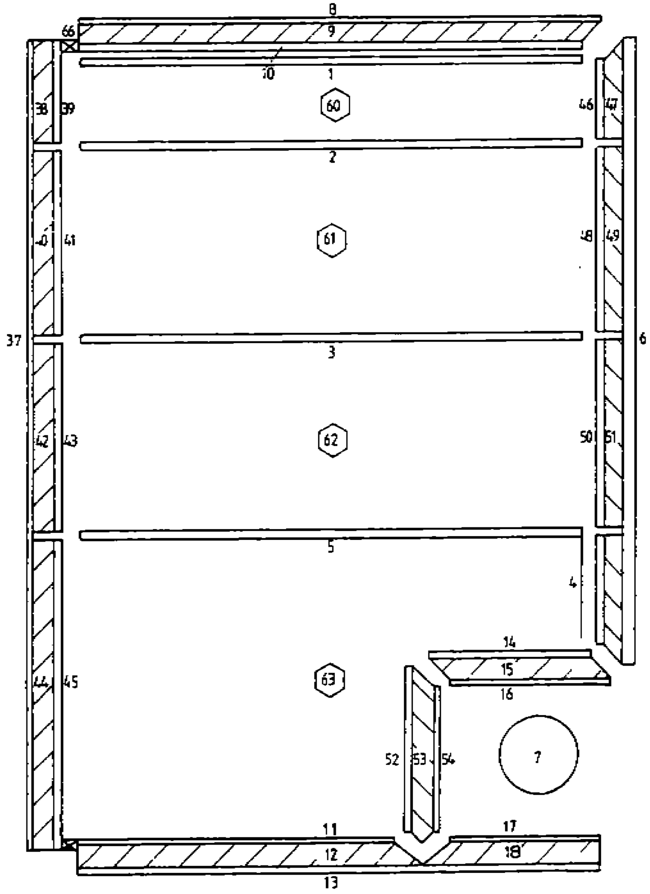

Fig. 8 : Model of a freezer

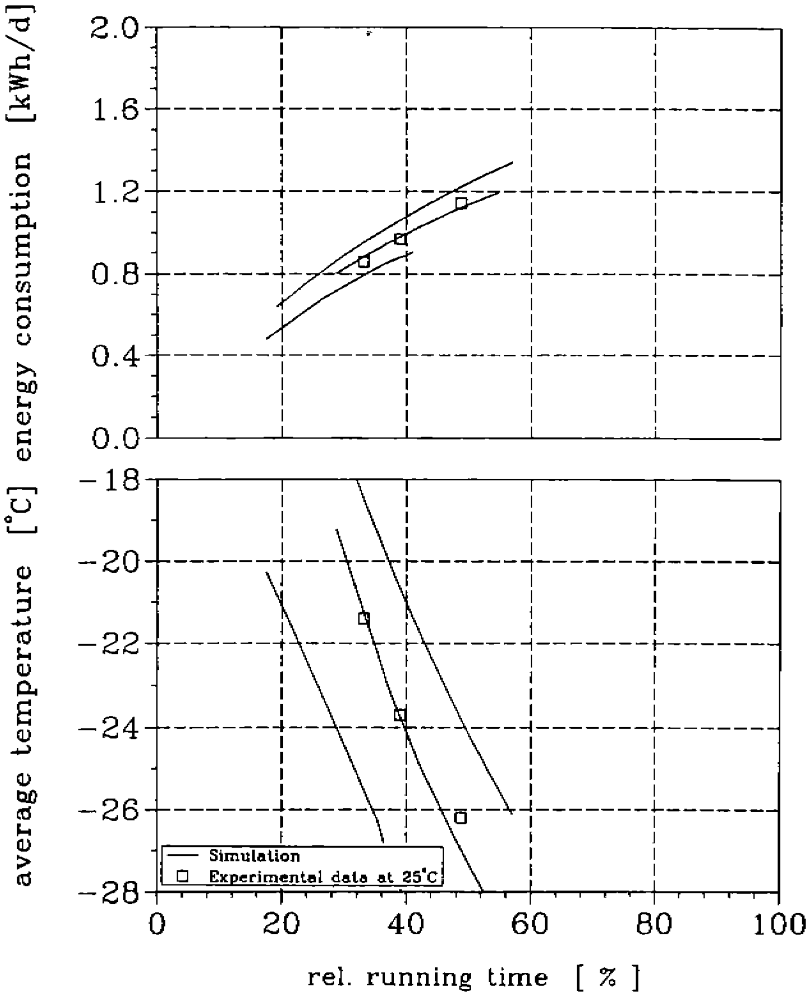

Fig. 9 : Comparison of experimental and calculated data for the freezer.