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Development and Validation of Refrigerator-Freezers Energy Consumption Model with the Aid of RSM

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Abstract

The understanding on energy consumption behavior of household refrigerator cabinet can be used as a guideline to increase energy efficiency of this appliance. This study investigated the effect of ambient temperature, loading in freezer compartment and frequency of door opening on the energy consumption of a frost free household refrigerator-freezer. The experiments were conducted in the laboratory and a first-order response model was developed utilizing factorial design of experiment and response surface methodology (RSM). The adequacy of the response model has been judged by the analysis of variance (ANOVA) at 95% confidence interval.

The study reveals that there is no interaction between the factors, and the factors exhibit significant main effect. The ambient temperature has the highest effect on energy consumption, followed by loading in freezer compartment. Frequency of door openings has the lowest effect on energy consumption. Based on the response model, contours have been plotted in loading–door openings planes. The contours help to predict the usage conditions for optimum energy consumption.

Nomenclature

b	matrix of parameter estimates
C	constant
D	door opening
DF	degree of freedom
E	estimated energy consumption (Wh)
E_o	observed energy consumption (Wh)
F_{cal}	F-test value by calculation
k, l, m	exponentially determined constants
MS	mean square
SS	sum of square
T	ambient temperature
W	loading in freezer compartment
x	matrix of independent variables
x^T	matrix of independent variables
$(x^Tx)^{-1}$	inverse of (x^Tx)
y	observed energy consumption = $\ln E_o$
$\hat{y}$	estimate value of y
β	parameters
ε	experimental error

Introduction

The rapid growth of the ownership of household refrigerator-freezer in Malaysia has increased year by year along with the total electricity consumption of the country [1]. In terms of energy consumption, it is almost the largest single end user of electricity in the residential sector due to its widespread use (76% houses in Malaysia [2] and continuous operation (24 hour operation). Thus, improved energy efficiency by implementing energy efficiency standards and labeling is important for energy saving issue.

The energy efficiency standards and labeling are to encourage consumer to use more efficient units, and thus eliminate the least efficient products from market. There are a number of test standards for domestic refrigerators being used around the world [3]. However the standards are not suitable for every country due to the different climate and utility. More study should be done regionally to understand energy consumption behavior of the refrigerator. The parameters that affect the refrigerator-freezer energy consumption greatly have been investigated.

The previous studies [4-8] show that there are many factors that affect the refrigerator-freezer energy consumption. These studies were limited to investigate the effect of single variable on energy consumption. In other words, they practiced the one-factor-at-a-time approach in which each factor was varied over its range while keeping the other factors constant.

In contrast to them, a first order mathematical model has been developed by Saidur *et al.* [9] to investigate the combined effect of ambient temperature, frequency of door opening, and thermostat setting position on energy consumption. In this study the combined effect on energy consumption has been studied but with different usage conditions factors, namely ambient temperature, loading in freezer compartment, and frequency of door opening. The model was obtained using response surface methodology (RSM) and factorial design of experiment. Moreover, adequacy of the model has been investigated in this paper using analysis of variance (ANOVA) while no model adequacy was carried out in the previous study [9]. A contour plot was also made in this study.

RSM is a collection of mathematical and statistical techniques, useful for analyzing a problem in which several independent variables influence a dependent variable or response, and the goal is to optimize this response. When experiments involve a study of the effect of multiple factors, factorial designs are most efficient tools to investigate their combined effect on a response [10]. ANOVA refers to the theory and procedures for analyzing the scores of an experiment. The general purpose of ANOVA is to determine the factors of an experiment that have noteworthy effects on the scores, and provide quantitative information about the relative importance of different factors and their levels [10, 11].

Mathematical Model and Error Analysis

The functional relationship between response (energy consumption) of the refrigerator and investigated independent variables (ambient temperature *T*, loading in freezer compartment, *W* and door opening, *D*) can be represented by following equation:

$$E = CT^{k}W^{l}D^{m} \tag{1}$$

or written as $\ln E = \ln C + k\ln T + l\ln W + m\ln D$ (2)

which may represent the following linear mathematical model:

$$\eta' = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3}$$

where η' is the true modeled energy consumption on a logarithmic scale, $x_0 = 1$ (a dummy variable), x_1, x_2,x_3, is the logarithmic transformation for T, W, and D, while β_0, β_1, β_2, β_3 are the parameters to be estimated.

Equation (3) can be written as

$$y - \varepsilon = \hat{y} = \sum_{i=0}^{3} b_i x_i \tag{4}$$

where y is the observed energy consumption on a logarithmic scale, $\hat{y}$ is the estimated response, ε is a random error, and the b values are estimates of the β parameters.

Equation (4) is generally utilized in RSM problems. The matrix approach of solving it is explained in [10], where the b values are estimated by the method of least squares. The basic formula is

$$b = (x^T x)^{-1} x^T y \tag{5}$$

y is defined to be a (n x 1) matrix on a logarithmic scale, **x** to be a (n x m) matrix of independent variables, b to be a (n x 1) matrix. The solution of this matrix can be performed using MATLAB.

The adequacy of first order model represented by Equation (4) has been tested by the analysis of variance (ANOVA).

Experiment Work

Experiment set-up and instrumentation

The test unit is located in a controlled chamber. The technical specifications of the refrigerator-freezer are presented in Table 1.

Table 1 Technical specifications

Freezer capacity (liter)	130
Fresh food compartment capacity (liter)	330
Power rating (W)	165
Current rating (A)	1.3
Voltage (V)	240
Frequency (Hz)	50
Number of door	2
Refrigerant type	R134a
Defrost system	Frost free

A heat pump was used to maintain a steady temperature within the environmentally controlled chamber in order to investigate the effect of ambient temperature variation. A hygro-thermometer clock was used for monitoring the ambient temperature and relative humidity.

Water in bottles (1.5 liter each bottle) was utilized as the loading in freezer compartment, due to the thermal properties of foods are dominated by their water content. The specific heat and the latent heat of food (there are cooling load of refrigerator) are calculated with reasonable accuracy on the basis of their water content alone [12].

An automated door opening and closing mechanism was developed. This mechanism consists of AC motor with a gearbox mounted on a steel frame at the top of refrigerator-freezer. The mechanical arms have been designed to connect both doors so that open and close subsequently. The door opening process was controlled using the Programmable Logic Controller (PLC). Programming is achieved using ladder logic. Operating switch, which is an input device, sends signals to the control the mechanism. Total run time, opening time and closing time are inserted into the operating switch. Each time the doors were set to remain open for 15 sec at an angle of 90^o. One opening with one closing is considered one cycle of the mechanism. The total run time for each experiment was set to be one hour.

Power consumption was measured by digital power meter, which was interfaced with PC. Labview software was installed on the PC for data storage and analysis. The complete experimental set-up is shown in Fig. 1.

Experiment design and results

Twelve experiments have been performed to develop the first order mathematical model. Eight experiments represent a factorial design, and the remaining four represent repetition to estimate the pure error. A factorial design of experiment is one in which all levels of a given factor are combined with all levels of every other factor in the experiment. Furthermore, factorial designs allow the effects of a factor to be estimated at several levels of the other factors, giving conclusions that are valid over a range of experimental conditions. The 2^k factorial design for multivariable tests have shown in Table 2.

According to the ref. [13] the transforming equations for each of the independent variables are

$$x_1 = \frac{\ln(T) - \ln(23)}{\ln(30) - \ln(23)} \quad x_2 = \frac{\ln(W) - \ln(9)}{\ln(24) - \ln(9)} \quad x_3 = \frac{\ln(D) - \ln(2)}{\ln(4) - \ln(2)} \tag{6}$$

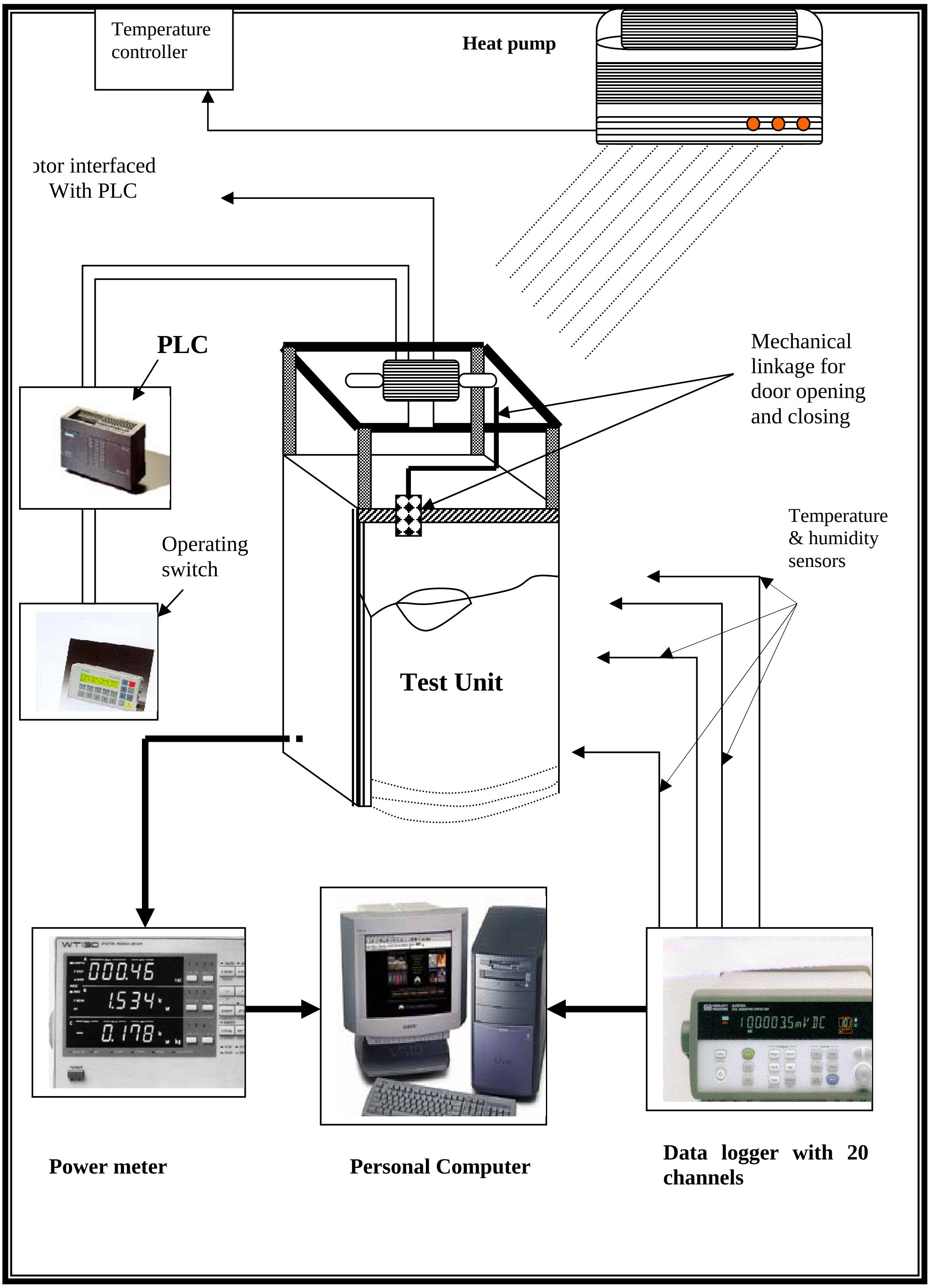

Fig.1 Schematic diagram of experimental set-up

Table 2 Experimental design and coding identification

Trial no.	T (^{0}C)	W (kg)	D (cyc/hr)	Coding x_1	x_2	x_3	E_o (Wh)	$y = \ln E_o$
1	18	3	1	–1	–1	–1	148.1	4.9979
2	30	3	1	+1	–1	–1	163.7	5.0980
3	18	24	1	–1	+1	–1	157.4	5.0588
4	30	24	1	+1	+1	–1	179.8	5.1918
5	18	3	4	–1	–1	+1	149.5	5.0073
6	30	3	4	+1	–1	+1	165.8	5.1108
7	18	24	4	–1	+1	+1	159.8	5.0739
8	30	24	4	+1	+1	+1	182.7	5.2078
9	23	9	2	0	0	0	161.7	5.0857
10	23	9	2	0	0	0	162.9	5.0931
11	23	9	2	0	0	0	162.7	5.0919
12	23	9	2	0	0	0	163.2	5.0950

Analysis and Discussion

Fitting linear regression model and ANOVA

The estimated energy consumption based on the 12 experimental results (Table 2) in coded form is

$$\hat{y} = 5.0927 + 0.0588x_1 + 0.0398x_2 + 0.0067x_3 \qquad (7)$$

Thus, by rearranging eq. (7) with (6), the estimated response (energy consumption), *E* in logarithmic equation can be written as:

$$\ln E = 4.3027 + 0.2214 (\ln T) + 0.0406 (\ln W) + 0.0096 (\ln D) \qquad 8)$$

In the form of estimated energy consumption as a function of *T*, *W*, and *D*,

$$E = 73.8965\, T^{0.2214} W^{0.0406} D^{0.0096} \qquad (9)$$

The analysis of variance (shown in Table 3) at 95% confidence interval shows that the ratio of lack of fit to pure error is 6.6693, whilst the F-statistics is 9.01. Since $\boldsymbol{F_{cal}} < \boldsymbol{F_{tab}}$, there is no interaction between the factors, and the factors exhibit significant main effect. Hence the linear modal is adequate.

Table 3 Analysis of variance for significance of regression and residual in linear model

Source	*SS*	*DF*	*MS*	F_{cal}	F_{tab}	
Regression						
First-order	0.04070	3	0.01357	186.3945	4.07	Significant
Residual	*0.0005823*	*8*	*0.0000728*			
Lack of fit	0.0005342	5	0.000107	6.6693	9.01	Not significant
Pure error	0.0000481	3	0.000016			
Total	0.0413	11				

Equation (9) indicates that the energy consumption increase with increase of ambient temperature, loading in freezer compartment and frequency of door opening. It was also noted that ambient temperature has the highest effect on energy consumption, follow by the loading in freezer compartment, and the frequency of door opening has the lowest effect.

Analysis on response contour plot

Figs. 2, 3 and 4 show the contours at four different ambient temperatures. These contours help to predict the energy consumption in any zone of the experimental domain. From these contour plots, it is obvious that there are many combinations of *W* and *D* that will consume the same amount of energy.

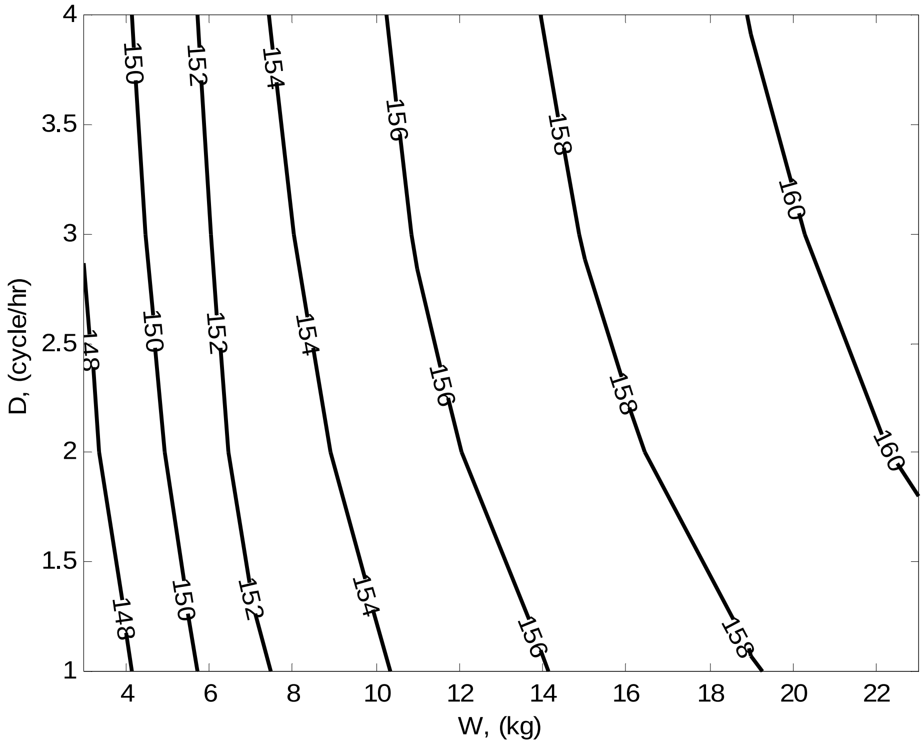

Fig. 2 Energy consumption contours in the *D-W* plane at ambient temperature 18 ^{o}C

It is clear from each of Fig. that the more energy is consumed with the increase of *W* at constant ambient temperature and constant frequency of door opening. However the rate of increase of energy consumption becomes lower as the *W* increase. The Figs. also indicate that only a small increase in energy consumption with the increase of *D* at constant T and constant W on the higher energy consumption region (about 1 Wh), but higher increase (about 2 Wh) on the lower energy consumption region.

Thus for the refrigerator-freezer that operated more efficiently (that is, use less energy), frequency of door opening has larger effect on energy consumption. These results suggest that measures to reduce the impact of door openings should be included among future design consideration. A trend of increasing energy consumption with the increasing ambient temperature is observed as with previous studies.

If the ambient temperature is held constant at lower level, as in Fig. 2, compared to the that held constant at higher level, as in Fig. 3, the same level of energy consumption is shifted towards the left and lower of the *W* axis, indicating that less loads can be put into the freezer compartment for the same energy consumption level.

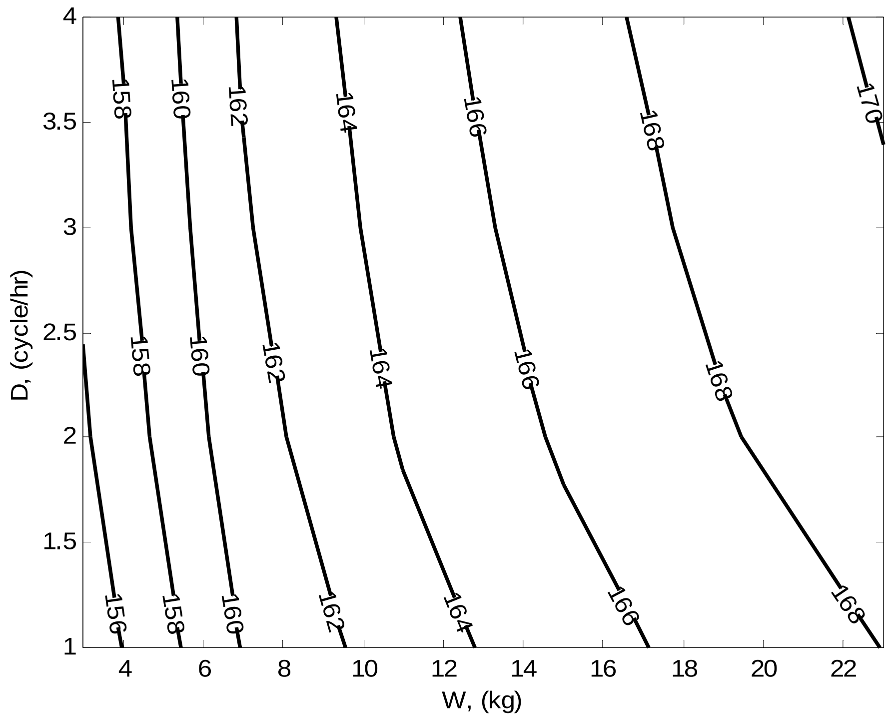

Fig. 3 Energy consumption contours in the *D-W* plane at ambient temperature 23 ^oC

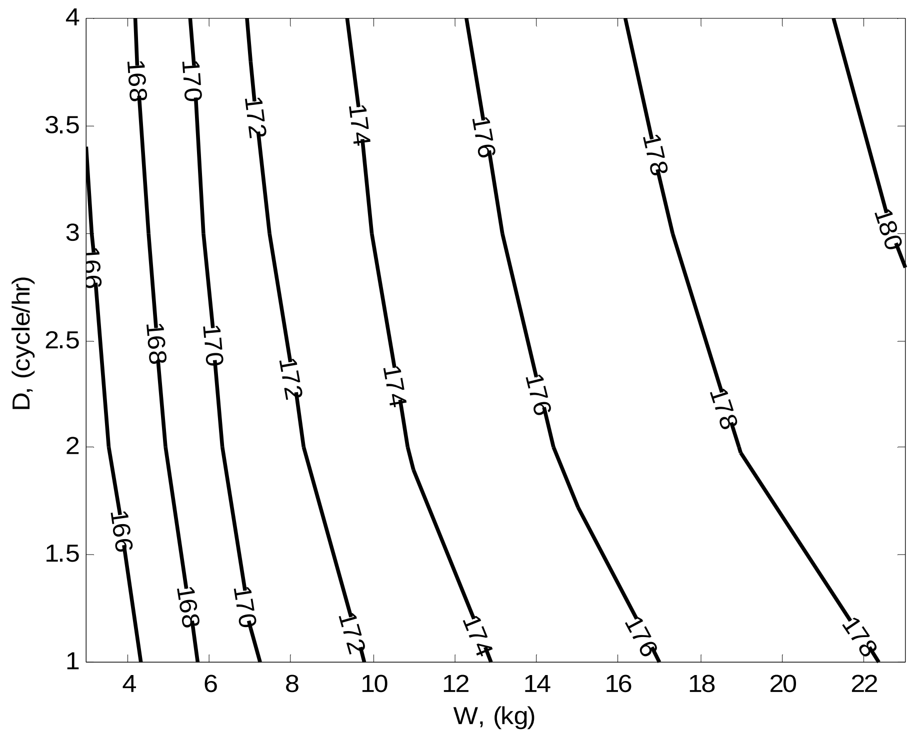

Fig. 4 Energy consumption contours in the *D-W* plane at ambient temperature 30 ^oC

Conclusion

The effects of ambient temperature, loading in freezer compartment and frequency of door opening on the energy consumption of a frost free household refrigerator-freezer have been investigated. The experiments were conducted in the laboratory and a first-order response model was developed utilizing factorial design of experiment and response surface methodology (RSM). The main findings are as follows.

i) The first-order model equation derived from this study shows that ambient temperature has the highest effect on energy consumption, followed by loading in freezer compartment and door opening.

ii) The adequacy of the model is proven by ANOVA that indicates that there is no interaction between the factors, and the considered factors exhibit significant main effect.

iii) The loading in the freezer compartment and door opening has low relative effect on energy consumption compared to ambient temperature.

iv) The energy consumption can be reduced by improving natural ventilation to keep the surrounding cool or locating the refrigerator-freezer at a place that is not exposed to direct sunlight.

All the experimental data were obtained from a single test unit. While the model of the refrigerator-freezer tested is only one of those currently marketed in Malaysia, it may not represent the performance characteristics of all models. Similar testing of several different models is recommended as a means of providing a more general analysis of refrigerator energy consumption.

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