Steady State Performance Variation of Domestic Refrigerators Under Different Ambient Conditions of Sri Lanka

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***Abstract*—There is a non-negligible variation in climatic conditions in different geographical locations of Sri Lanka. Testing the performance under single climatic condition will not reflect the actual performance of a refrigerator at its intended deployment. This research is aimed at studying the performance of a domestic refrigerator unit under simulated climatic conditions representing different climate zones in Sri Lanka with respect to its dry bulb temperature. Experiments were conducted under controlled environmental conditions to emulate the climatic conditions of different climatic zones in Sri Lanka. Average hourly power consumption under each climatic condition was calculated from the results. Projected annual energy consumption and performance of the overall refrigeration cycle were also estimated. Results indicated a 5.6% increase of energy consumption per 1℃ increase of ambient temperature. Annual power consumption shows 54.2% variation within the evaluated locations. A simulation model was developed to perform the evaluation. Existing mathematical model was adopted to calculate the performance of the refrigeration cycle.**

Keywords—Domestic refrigerators, Energy management, Refrigerating systems, Refrigerator performance modeling

I. INTRODUCTION

In recent decades, the domestic households (all-electrical appliances and lighting) have become a major consumer of electrical energy. In Sri Lanka, the electricity usage for domestic appliances is becoming increasingly widespread. In year 2010, the energy utilization for domestic appliances was 3,651.4 GWh, which is approximately 40% of the total energy demand of the country [3].

Among these appliances, refrigerators have become the most essential device for consumers because they improve the society's standard of living. In addition to domestic usage, it is also being used for minor commercial applications such as food preservation and medical applications. Presently, the usage of refrigerators has drastically increased due to the increase of disposable income of consumers, increase of electricity availability and decrease of cost of refrigerators [6]. Because of thegrowth of usage, the percentage of the total energy consumption for domestic refrigeration has ascended significantly. However, due to theround the clock operation, domestic refrigerators account for the highest electricity consumption among the electrical appliances. According to the Ministry of power and energy Sri Lanka, domestic Refrigerators consume 40% to 50% of the total generated electricity thereby utilizing more than 16% of the national energy supply [4]. There is a drastic increase in the unit cost of electricity generation in recent years. According to Central Bank (Sri Lanka) reports, consumer price index for electricity has increased by 12.6% during 2010 to 2012 [5]. Thus, the demand from government and general public for refrigerators to use minimum energy resources without sacrificing value to the consumer is very high. Therefore, the pressure is constantly on refrigerator manufacturers to investigate novel technological strategies to make the refrigerators more energy efficient.

Since the refrigerator is a significant contributor to home energy use, many countries and standard setting organizations have introduced performance standards and Minimum Energy Performance Standards (MEPS) for refrigerating appliances. These standards are generally developed through a consensus process with manufacturers, consumer groups and environmentalists. These Appliances can be brought into market only if they comply with the mandatory provisions of MEPS.

Performance of a refrigerator depends on two main contributing factors, namely thermal insulation of the refrigerator shell [13] and the heat rejection performance of the refrigeration cycle. The combined effects of those contributing factors were studied in this experiment. Both of these factors depend on the ambient temperature at which the refrigerator operates. Therefore, the performanceanalysis of a refrigerator operating under the varying ambient conditions is essentialto reduce its energy consumption under actual deployment.

II. METHODOLOGY

Refrigerator unit and measuring equipment were installed inside a test cell, where temperature surrounding the refrigerator can be controlled and maintained within a limit of

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± 0.5°C. The power consumption and temperatures at selected points of the refrigerator and its' cycle along with the temperature of the test cell were set into an automatic logger. Indicated gauge pressure of the refrigerator at specified time periods was recorded by two analog pressure gauges. Measurements were taken when the operating cycle of the refrigerator has reached a steady state. Steady state operation was identified by observing cabinet temperature and compressor operating cycle.

Readings were taken since the refrigerator was switched on. But the data for the calculations was obtained after achieving the steady state operation. Test results were used to calculate the power consumption for 1 hour operating time of the refrigerator at a set ambient temperature. Calculation was based on a finite number of complete operating cycles of the compressor during one hour operating period. Experiment was performed for 5 distinct ambient temperatures and results were used to interpolate the power consumption for ambient temperatures within the cell using a curve fitting technique under no load condition.

Actual hourly variations of ambient temperature [11] at selected locations were used to evaluate the predicted annual power consumption of the refrigerator. Hourly power consumption was interpolated based on the equation obtained by curve fitting. The annual electrical energy consumption was estimated by calculating the Sum of hourly power consumption. Six locations around the country were selected to represent the scattered refrigerator usage around the country. An existing model was adopted with a modification to predict the performance of the refrigeration cycle and individual components.

III. TEST CONDITIONS

A. Ambient Temperature

To conduct a performance study in Sri Lanka, the experiment must be performed under different climatic zones within Sri Lanka. Six key locations with different climatic conditions were selected as mentioned below. Location selection was based on the population and the mean ambient temperature [10] as shown in table 1.

TABLE 1. ANNUAL AVERAGE TEMPERATURE BY LOCATION

Location	**Annual Average Temperature (^{0}C)**
Anuradhapura	28.3
Katunayake	27.7
Ratmalana	28.3
Nuwaraeliya	16.1
Puttalam	27.9
Potuvil	28.3

Nominal test conditions in Sri Lanka lie between 16°C and 30°Caccording to the temperature distribution indicated above. Table 1 exemplifies only the average temperature values which do not represent the high and low extreme values that can occur during day and night. However, these values need to be addressed because the power consumption of the refrigerator does not vary linearly with the ambient temperature. Therefore test ambient temperatures for the present study were selected between 15°C and 35°C.

B. Cabinet Type

There are three main types of refrigerator cabinets available in the market. They are

1. All refrigerators
2. Refrigerator – Freezer
3. Freezer

Among the three models, refrigerator – freezers is the most convenient model for consumers because of the combination of refrigerator and freezer compartments. Due to this reason, this type of refrigerators is mostly available in the local market. Therefore, the experiments in the present study were focused on refrigerator-freezer units.

C. Cabinet Temperature

Domestic refrigerators have a star rating according to the minimum temperature which its freezer compartment can achieve [2]. Refrigerator is tested with respect to a one star refrigerator cabinet because it represents the common operating conditions of household refrigerators. Even though the tested refrigerator is a two star type, the selected test conditions was matched with actual usage conditions. According to D.D.A.Namal and K.G.C. Jayasekara [8], only 20% of the domestic refrigerator users utilize high setting of thermostat control. This implies that these refrigerators are operated well below their designed lowest cabinet temperature [8] [17]. The refrigerator unit used in the present study was set to 2/7 of full scale of thermostat control setting. Most of the domestic users do not utilize higher freezing levels in order to reduce electricity consumption. Therefore similar strategy was adopted in deciding the operating temperature of the refrigerator.

D. Loading and Door Openings

According to ANS and ISO standards, the freezer cabinet should be loaded during the experiment [2], whereas the other standards do not require this criterion in testing. Number of door openings and loading conditions under steady state operation, does not have considerable influence over the steady state performance and influence only on its performance at transient operation. Loading will have significant impact on the result if fresh loads were introduced during the testing [1] [14]. It is unlikely that the users insert new items into the refrigerator in a regular basis. Door openings have a significant influence over the energy consumption [16]. But the manufacturers do not have control over usage and loading conditions of the customer and therefore most of the standards do not require testing for door openings and loading. Therefore the present experiment was performed without door openings and loading.

TABLE 2. DETAILS OF REFRIGERATOR UNIT

Parameter	Value
Displacement (cm^3)	5.1
Clearance ratio	0.028
Power (W)	123
COP (As per compressor manufacturer)	1.12
Freezer volume(cm^3)	24 l
Fresh food compartment volume(cm^3)	132 l

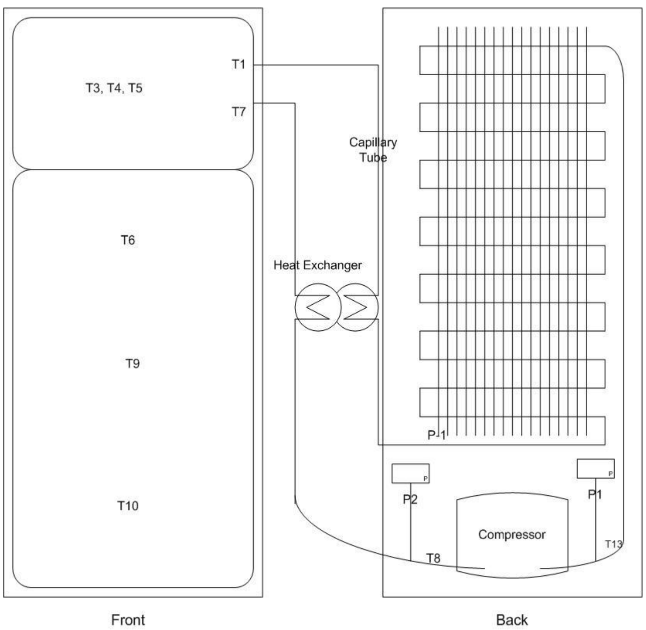
E. *Refrigerator Unit*

The selected refrigerator operates onR134a refrigerant, reciprocating compressor and a capillary tube expansion device. Evaporator is located at a 3 cm distance outside the back wall of the refrigerator. The details of the compressor and the refrigerator cabinet are illustrated in Table 2. Clearance ratio of the compressor was calculated by applying manufacturer specified data test conditions on equation 1.

F. *Refrigerator Test Cell*

Refrigerator test cell was designed and constructed to maintain a set temperature required to perform the experiment according to the test standards. The test cell was equipped with a split type air conditioner combined with a heating system to obtain the required ambient temperatures. Both heating and cooling equipment were locatedsuch that their induced draft has minimal interference on refrigerator unit.

Fig1. Schematic of the refrigerator unit showing points of temperature and pressure measurements



G. *Instrumentation*

Figure 1 shows the points where the temperature readings were taken in the refrigerator unit. T type thermocouples with accuracy of 0.1^{0}C were used to measure temperature with a temperature logger. Hoboware data loggers were used to measure the ambient temperature inside the test cell. Power consumption of the refrigerator unit was monitored using PZ4000 power analyzer. According to the manufacturer's literature, the readings have an accuracy of 0.1%. Temperature readings were logged at intervals of 30s and the power consumption was recorded at every 3.5s intervals. Operating pressure of the Low and high pressure sides of the refrigerator were recorded using two analogue pressure gauges. High pressure gauge had an error of 5 psi whereas the low pressure gauge had an error of 1 psi. [15] [9]

IV. CALCULATION AND RESULTS

Several critical measures were identified to evaluate the performance of a refrigerating unit. As mentioned previously, performance of a refrigerator depends on refrigeration cycle's performance and insulation quality of the refrigerator cabinet. Operating parameters were observed for the steady state intermittent operation where the compressor on-off cycles were occurring steadily and the cabinet internal temperature variations were steady. An existing semi empirical model [l] was adopted to evaluate the refrigeration cycle.

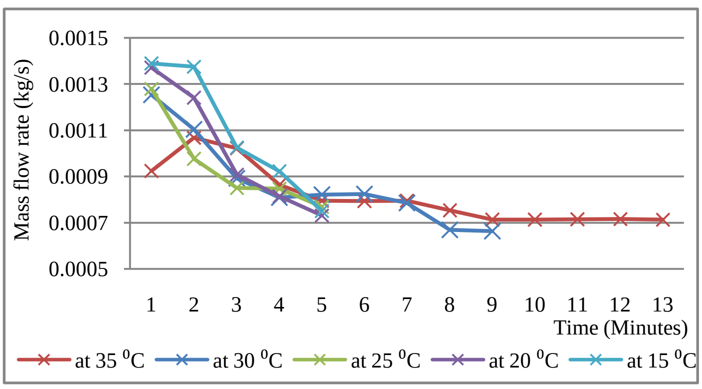
A. *Mass Flow Rate of the Refrigerant*

Refrigerant mass flow rate was calculated using an empirical equation as suggested by Cezar at el (2008) [9]. Mass flow rate is required to calculate the transfer of thermal energy through the evaporator. Equation for the calculation of refrigerant mass flow rate is given in equation 1 [15].Pressure ratio (PR) of the compressor was calculated by measuring inlet pressure (P1) and outlet pressure (P2) of the compressor. Clearance ratio (C)and the swept volume (V) of the compressor were found according to the manufacturer's specifications.

$$\dot{m} = V \times n \times \rho \times \{1 - C[(PR)^{1/k} - 1]\} \qquad (1)$$

n is the operating frequency of the compressor and ρ is the density of the refrigerant entering the compressor.For all the calculations, properties of the refrigerant were obtained using NIST Refpropdatabase[12].

Figure 2: Refrigerant flow rate per operating cycle



B. *Electrical Energy Consumption of Compressor*

TABLE 3HOURLY POWER CONSUMPTION AT TEST CONDITIONS

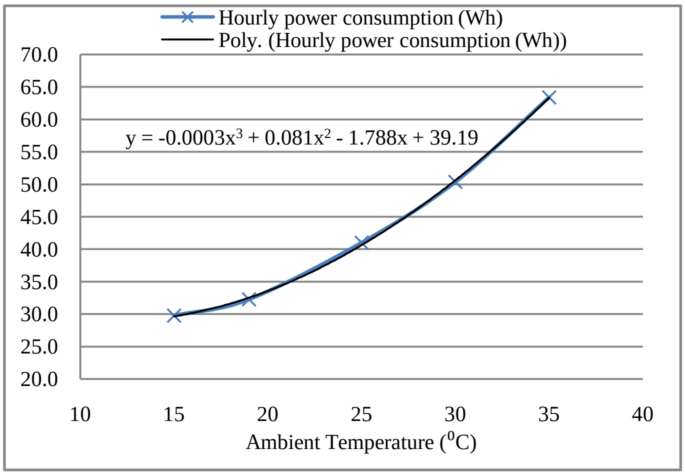
Ambient Temperature (^{0}C)	Compressor Cycle Time (s)	On Time (%)	Hourly Power Consumption (Wh)
35	1320	59.09	63.41
30	1110	45.95	50.36
25	900	38.00	40.99
19	1056	30.30	32.26
15	1108	27.80	29.75

Power consumption of the compressor was recorded by using a PZ4000 power analyzer. Power consumed per compressor on-off cycle and time duration of the compressor cycle was calculated. Calculation error was minimized by averaging the results taken for three complete compressor operating cycles. Per cycle power consumption was then used to calculate the hourly power consumption of the refrigerator unit under the given ambient temperature. Results of this calculation are given in table 3.

C. *Annual Power Consumption*

Table 3 illustrates the hourly power consumption of the refrigerator measured at the ambient temperatures.Main objective of this paper is to identify the projected annual power consumption under existent conditions at certain geographical locations in Sri Lanka. Hourly weather data available for the nine different locations in Sri Lanka were obtained from the Department of Energy, USA web site [11]. Six locations were selected for further analysis. Results presented in table 3 were plot in a graph (figure 2) and a curve fitting technique was employed to derive a relation between power consumption and ambient temperature. The resulting curve fits to the degree of 3rd order polynomial given in equation 2.

Fig. 2.Hourly power consumption of the refrigerator unit as a function of ambient temperature



Equation 3 was then used to derive the hourly power consumption at temperatures between 15 ^{0}C 35 ^{0}C and up to 38^{0}C. Annual power consumption for a selected location was calculated using hourly weather data and equation 2 to calculate power consumption at the ambient temperature of each hour.

$$y = -0.0003x^3 + 0.081x^2 - 1.788x + 39.19 \tag{2}$$

Figure 3 shows the projected annual power consumption for the ambient conditions in six different locations in Sri Lanka.Heat Gain through Refrigerator Walls

In addition to the refrigeration cycle, it is also important to evaluate the heat gain through the walls of the refrigerator. It can be shown that heat gain is equal to the heat absorption of evaporator at the steady state level of operation by applying energy balance to the system. Heat gain through conduction was calculated by applying Newton's law of cooling.

$$Q_f = UA\,(T_f - T_a) \tag{3}$$

Combined valueof the overall heat transfer coefficient and effective heat transfer area of the refrigeratorcabinet (UA) was estimated by placing a heat source of 72 W inside the refrigerator and monitoring internal and external temperatures at the steady state. But this value could not be applied directly to the operating conditions because the temperature distribution within the refrigerator is not uniform during the operation. This was corrected by treating freezer and fresh food compartment as separated volumes with their respective internal temperatures and the external wall temperature was assumed to be uniform around the refrigerator cabinet.

Figure 3 Projected annual power consumption at selected locations

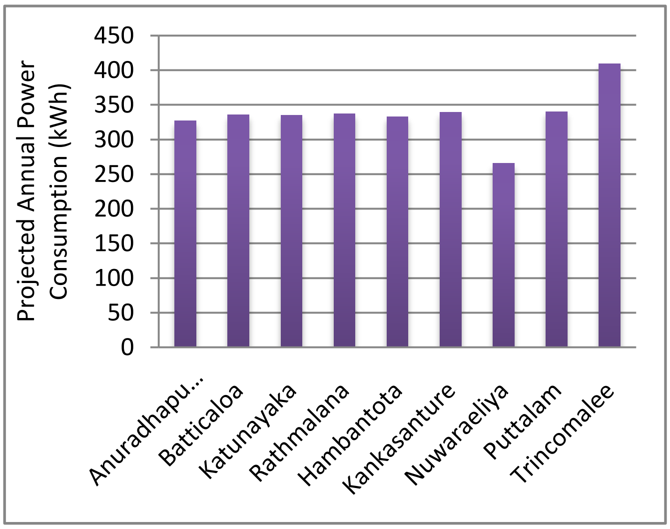


TABLE 4. HOURLY HEAT GAIN THROUGH REFRIGERATOR SHELL COMPARED TO HOURLY POWER CONSUMPTION

Ambient Temperature (°C)	Hourly Heat Gain (Wh)	Power Consumption (Wh)
35	64.80	63.41
30	56.60	50.36
25	47.93	40.99
19	39.58	32.26
15	26.04	29.75

Table 4 compares the projected hourly power consumption with the calculated hourly heat gain through the refrigerator shell at different operating temperatures.

V. CONCLUSION

Experimental results indicate a significant increase in mean hourly power consumption with respect to the changes of its surrounding dry bulb temperature hence causing a decreaseofthe calculated COP of the refrigeration cycle. Similarly, calculated mean hourly heat gain through the refrigerator shell also increases with the increase of ambient temperature in line with the energy balance applied to the refrigerator at the steady state operation. These results imply an important insight to the refrigerator manufacturers and end users. The trends of these results can be conveniently used to decide on the economic level of refrigerator shell insulation. Because of the variation of temperature occurring in Sri Lanka, refrigerators will operate with significant variation in energy performance. The trends of these results can thus be used to provide guidelines for refrigerator placing in building interiors and also reconsider condenser designs of local manufacturers.

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