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MOISTURE TRANSFER AND ENERGY LOSSES OF HOUSEHOLD REFRIGERATOR-FREEZER DURING THE CLOSED DOOR OPERATION

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ABSTRACT

This paper presents the moisture transfer and energy losses due to moisture of household refrigerator-freezer during the closed door operation. Moisture transfer into the cabinet takes place by two ways of gasket diffusion and cabinet breathing. Experiments were conducted in the controlled chamber to investigate the effects of the ambient temperature, cabinet load, thermostat set position and open surface water pan area inside the cabinet on moisture transfer. The average gasket diffusion and cabinet breathing moisture transfer is about 4.6 kg/year and 18 kg/year respectively. In this experimental investigation, it is found that the average energy consumption of the refrigerator-freezer in kWh/day is about 2.9, 2.8, 2.8 and 2.9 due to the ambient temperature, cabinet load, thermostat set position and open surface water pan area respectively. The ambient temperature and open surface water pan area inside the cabinet have strong influence on gasket diffusion and cabinet breathing moisture transfer respectively. The extra energy consumption due to the gasket diffusion and cabinet breathing moisture transfer has been calculated and found as 1.3 kWh/year and 4.9 kWh/year respectively. The ambient temperature and cabinet load has strong influence on energy consumption compared to the thermostat setting position and open surface water pan area inside the cabinet. The average energy consumption is about 1043 kWh/year of the refrigerator-freezer.

Keywords: Energy consumption; Moisture transfer; Gasket diffusion; Cabinet breathing.

1 INTRODUCTION

Energy is one of the indispensable factors for continuous development and economic growth. The demand of energy is increasing rapidly in the developing countries due to automation, industrialization and urbanization. Rahman Mohamed and Lee (2006) investigated that the energy demand in Malaysia is increasing rapidly and the energy demand increased almost 20% within the last 3 years (from 1999 to 2002). The energy demand is further expected to increase almost 60% within 8 years (from 2002 to 2010). Varman *et al.* (2005) predicted that residential electricity consumption will increase in 27,053 GWh in 2015. Refrigerator-freezer is one of the most essential appliances to preserve perishable foods in a household. Keeping foods fresh and freezing the perishable food are the basic functions of household refrigerator-freezer. It is operated and consumes energy for 24 hours continuously. Mahlia *et al.* (2004) conducted a survey and investigated that in Malaysia the number of refrigerator-freezer increased from 175,842 units in 1970 to 4,196,486 units in 2000. From the survey, it is also estimated that electricity consumption has increased from 326 GWh in 1970 to 9,471 GWh in 2000 in the residential sector. Liu *et al.* (2004) stated that the energy consumption of refrigerator-freezers was about 15% to 20% of total domestic electric usage. Mahlia *et al.* (2003) investigated that refrigerator-freezers consumed about 26% of residential electricity in Malaysia. Reddy and Balachandra (2003) investigated that residential sector of India consumed about 39% of total energy in 2000.

Nowadays most of the people use refrigerator-freezers as a vital household appliance to keep food fresh. Razali *et al.* (1993) conducted a survey to investigate household energy patterns and revealed that about 76% of total residential houses were equipped with one refrigerator-freezer in Malaysia. In some cases, they showed a multiple number of refrigerator-freezers owned by a single house owner. Users pay attention to the refrigerator-freezer's capability to keep food fresh as well as its energy consumption. Energy consumption of refrigerator-freezer also depends on the ambient temperature, relative humidity, thermostat set point, and food loading etc. Meier (1995) investigated that energy consumption varied from 1.25 kWh/day to 2.6 kWh/day for an 11ºC increase in temperature. Gage (1995) investigated door opening and energy consumption on nine refrigerator-freezer units from a variety of households. The average number of door openings per day per person was found to be 10 for fresh food and 3 for freezer while the length of the openings was an average of 10 seconds. Refrigerator-freezer consumes

1.4 kWh/day more energy in 26 door opening compared to no door opening. Saidur *et al.* (2002) performed an experiment to determine the effects of room temperature, thermostat set position and door opening on the energy consumption. Room temperature has the greater effect on energy consumption, followed by door opening and thermostat set position. The door opening and thermostat set position have a little difference in their relative effect on energy consumption.

Inan *et al.* (2002) investigated moisture transport in domestic refrigerator in the period of door opening 20 seconds, with 10 seconds of initial air exchange and 10 seconds of steady airflow at the surrounding ambient condition of 30 ^{o}C and 50% relative humidity. Approximately 60 kg of water vapor transport was found in a year with 20 door openings per day and extra energy 100 kWh/year was consumed.

Stein *et al.* (2002) performed an experiment of closed door moisture transport in refrigerator-freezers. Gasket infiltration is the function of the difference in water vapor partial pressure between the fresh food and freezer cabinets and the outside air. Meier and Jansky (1993) investigated the field performance of refrigerator compare with the laboratory test and collected 432 refrigerators data. Few technical problems and wide distribution of energy usage, 209 refrigerators were compared with their labeled consumption analysis. The mean measured energy use of the 209 refrigerators was 1009 kWh/year where the mean labeled energy use was 1160 kWh/year.

Grimes *et al.* (1977) performed an experiment on the effect of usage condition on energy consumption of household refrigerator-freezer. Ambient temperature and thermostat setting position were found to have considerably greater effect on energy consumption than door opening and relative humidity variation. Increasing ambient temperature from 23.9 ºC to 32.2 ºC increased daily energy consumptions from 22% to 42% in close door condition. Most of the users keep refrigerator-freezers in the kitchen and some time near the cooker or burner. If the ambient temperature is comparatively high, the temperature different between the ambient and refrigerator-freezer compartment is increased. More heat is transferred through the walls to compartment as well as increase energy consumption.

The aim of the research is to investigate the effects of operating environmental conditions on the moisture transfer and energy consumption and the trends of energy consumption due to the different operating conditions, gasket diffusion and cabinet breathing moisture transfer of the refrigerator-freezer.

2.0 RESEARCH METHODOLOGY

2.1 Experimental setup

This section provides a description of the test conditions and facilities developed for conducting experimental work on a domestic refrigerator-freezer. Experiments were conducted at Energy Conservations Laboratory, University of Malaya.

2.1.1 Test conditions

The tests were conducted by varying ambient temperature, cabinet load, thermostat setting position and open surface water pan area independently during the closed door conditions. During the experiment, only one variable was changed and the other variables were kept constant. To investigate the effect of the ambient temperature on moisture transfer and energy consumption, temperature was varied from 18 ºC to 30 ºC in the environmentally controlled chamber. Fresh food and freezer cabinets were loaded to investigate the effects of load and the load was varied from 0 kg to 8 kg and 0 kg to 4 kg of fresh water in the fresh food and freezer cabinet respectively. The thermostat set position was changed from 1 (-13.1 ºC) to 5 (-17.5 ºC) to reveal the effects of cabinet temperature. Open surface water pans were used to create wetted surface in the fresh food cabinet. In this work, water pan area was varied from 324 cm^2 to 1272 cm^2.

2.1.2 Test unit

The refrigerator-freezer used was top mount freezer section, two doors and both doors hinged at right hand side. The specifications of the refrigerator-freezer are shown in the following table.

Table 1 Technical specifications of refrigerator-freezer test unit

Specifications	Rating
Freezer capacity (liter)	130
Fresh food compartment capacity (liter)	330
Power (W)	165
Current (A)	1.3
Voltage (V)	240
Frequency (Hz)	50
No of door	2
Refrigerant type	134a(CF_3CH_2F)
Defrost system	Frost free

2.1.3 Location of thermocouples and humidity sensor

Thermocouples were used to measure temperatures inside and outside walls, doors, fresh food cabinet, freezer cabinet and ambient air. The location of thermocouples and humidity sensor are shown in the Fig. 1. Four thermocouples were attached at the middle position of both walls to measure wall temperatures (positions 2-5) and one thermocouple aws attached at the middle (position 1) of cabinet separator in the freezer cabinet (Lacerda *et al.,*2005; Afonso and Matos, 2006). Similarly, six thermocouples were used in fresh food cabinets that were placed at both side of walls (positions 8-11) and the cabinet separators (positions 6-7). To measure temperatures at the outside of the walls and doors of refrigerator-freezer, the other six thermocouples were used (positions 13-15). Five thermocouples are set to monitor the ambient temperature inside the controlled chamber. Humidity sensor was used to measure the relative humidity of the fresh food cabinet and the controlled chamber.

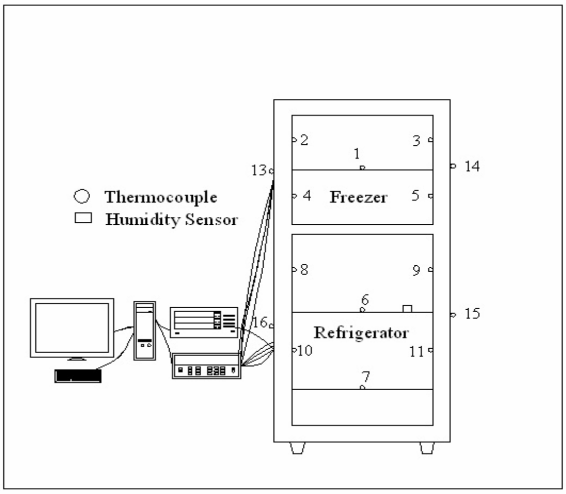

Fig. 1 Location of thermocouple and relative humidity sensor with the data acquisition system (Front view)

2.1.4 Location of load during closed door test

A load was used both in fresh food and freezer cabinet to make a real situation during the closed door test. Both the fresh food and freezer cabinets were divided into two shelves and each shelf contains same load. Open surface water pan was added in the fresh food cabinet that made the surface wet inside the refrigerator (Steain *et al.,* 2002). The location of open surface water pan and closed water bottle are shown in the Fig. 2. During the experimental investigation, the temperature of the water in fresh food and freezer cabinets was considered same as cabinet air temperature where the initial temperature of water was 25 ºC.

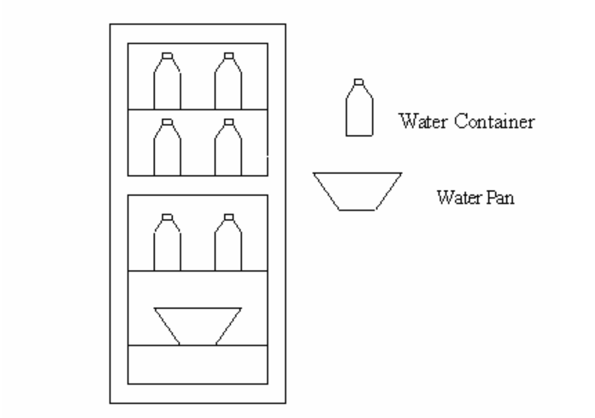

Fig. 2 Location of load during close door operation (Front view)

2.2 Instrumentation

The experiments were conducted in an environmentally controlled chamber. Some instruments were used to measure the temperatures, load, relative humidity and power consumption. To measure the temperature inside as well as outside the test unit, T-type thermocouples were used. Humidity transmitter was used to monitor the relative humidity inside the cabinet of the refrigerator-freezer. Relative humidity measurement range 3% to 95% and an accuracy of ± 5%. Heat pump was used to maintain the required temperature in the environmentally controlled chamber. The modes of operation of heat pump are heating, cooling and the temperature range from 16±1 ºC to 32±1 ºC. The temperature fluctuation was controlled by using a temperature controller. The controller was interfaced with the heat pump so that the desired temperature could be maintained within the chamber. To maintain relative humidity of the control chamber, dehumidifier was used and the range of dehumidifier from 0% to 90% with an accuracy of ± 5%. Electronic balance was used to weight the mass of evaporated water from the open surface water pans and cabinet load with weighing capability of 0.01g to 2 kg.

Hewlett Packard data logger was used to store the data from the test unit to personal computer for calculation and analysis. Two additional fused channels were included on the module for making calibrated DC or AC current measurement. The data logger supports direct measurement of temperature, AC voltage, DC voltage, AC current, DC current, resistance, frequency and period. Energy consumption was measured by the YOKOGAWA WT-130 digital power meter, which was interfaced with a PC through RS-232. Lab view software was installed into the PC for data storage and analysis. The accuracy of this power meter is ± 0.2% of reading.

2.3 Closed door moisture transfer

Moisture is transported during the closed door condition by gasket diffusion, cabinet breathing and various penetrations (condensate drain tube, perforation of wires and tubes etc). In the research the considering moisture transfer are gasket diffusion and cabinet breathing.

2.3.1 Gasket diffusion of moisture

Gasket is used at the refrigerator-freezer door to leak proof. Although gasket is used at the door, there are some small gaps between the gasket and cabinets / doors. Moisture is transferred from the relatively hot surrounding to the cabinets through the gaps. Stein *et al.* (2002) stated that the water vapor pressure difference between the cabinet interior and exterior environment drove the flow of moisture. The water mass flow rate per length of gasket is proportional to the water vapor pressure difference. Gasket diffusion moisture transfer is calculated by the following Equation.

$$\dot{m}_w = \bar{h}_m[L_{ff}(P_{wvamb} - P_{wvcab}) + L_{fz}(P_{wvamb} - P_{wvcab})] \quad (1)$$

where:

$\dot{m}_w$ = water flow rate
$\bar{h}_m$ = water vapor mass transfer coefficient
L_{ff} = gasket length of fresh food cabinet
L_{fz} = gasket length of freezer cabinet
P_{wvamb} = ambient water vapor pressure
P_{wvcab} = cabinet water vapor pressure

Inan *et al*. (2002) investigated the gasket diffusion moisture transfer and formulated to determine the water vapor mass transfer coefficient. The water vapor mass transfer coefficient ($\bar{h}_m$) is calculated by the following Equation.

$$\bar{h}_m = \left(\frac{\rho D t}{w P_{tot}}\right)\left(\frac{MW_w}{MW_{tot}}\right) \quad (2)$$

where:
D = water vapor diffusivity in air
ρ = air density
MW_{tot} = air-water mixture molecular weight
MW_w = water molecular weight
t = assumed gasket gap
w = gasket width

2.3.2 Cabinet breathing

Cabinet breathing is occurred due to the on-off cycle of the refrigeration system. The refrigerator-freezer cabinets are in pressure equilibrium with their surroundings because of the various cabinet penetrations. They are alternately cooled and warmed up during on-off cycle. Fresh foods and liquid water are the sources of cabinet breathing. Inan *et al.* (2002) mentioned that during the "on" cycle the cabinet was cooled, air might be pulled into the fresh food compartment and in the "off" cycle, the cabinet contents were warmed up and the air might be exhaled through the freezer. Cabinet breathing moisture transfer is calculated from the difference between the weight of the open surface water pan in the cabinet before starting the experiment and after ending the experiment.

3.0 RESULTS AND DISCUSSIONS

3.1 Moisture transfer during the closed door condition

Moisture transfer during the closed door condition depends on some factors such as operating condition and structural condition. Operating condition is an important factor to reduce moisture transfer as well as energy consumption. If the refrigerator-freezer is more loaded or more temperature difference exists, the compressor on-off cycle and operation time get larger to maintain the desired temperature of the fresh food and freezer cabinet. Cabinet breathing and gasket diffusion are affected by the compressor on-off cycle and operating time. Gasket diffusion moisture transfer also depends on the gasket properties. But in the research, the gasket was same for all the experiment.

3.1.1 Effect of ambient temperature on moisture transfer

Ambient temperature is an important factor of the refrigerator-freezer to keep fresh food fresh. Bansal (2003) studied various test standards and investigated that fresh food and freezer cabinet temperature are mostly in the range of 3 ºC to 5 ºC and -15 ºC to -18 ºC respectively. When the ambient temperature is comparatively high, the temperature difference between the ambient and the cabinet is also high. Water vapor pressure is proportional to the temperature. Inan *et al.* (2002) investigated that the water mass flow rate of gasket was proportional to the water vapor pressure difference. If the ambient temperature increases, gasket diffusion moisture transfer increases too. Fig. 3 and Fig. 4 show the gasket diffusion and cabinet breathing moisture with changing in ambient temperature. In this work, the gasket diffusion moisture transfer is increased from 7.4 gm/day to 18.4 gm/day when the ambient temperature increases from 18 ºC to 30 ºC. Gasket diffusion moisture transfer increases around 0.9 gm/day for 1 ºC increase in ambient temperature. With an increase of the ambient temperature, the compressor operating time and the on-off frequency increase. Hence the cabinet breathing increases with the rising ambient temperature. The cabinet breathing is found to be increased from 27.1 gm/day to 68.2 gm/day when the ambient temperature increases from 18 ºC to 30 ºC. Cabinet breathing increases 3.4 gm/day for 1 ºC rise in ambient temperature. From Fig. 3 and Fig. 4, it can be stated that there is a strong influence of ambient temperature on moisture transfer of the refrigerator-freezer.

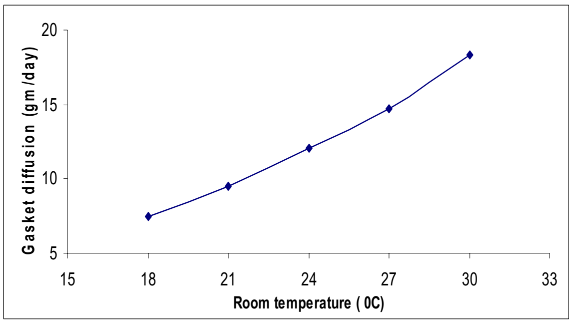

Fig. 3 Variation of gasket diffusion with ambient temperature

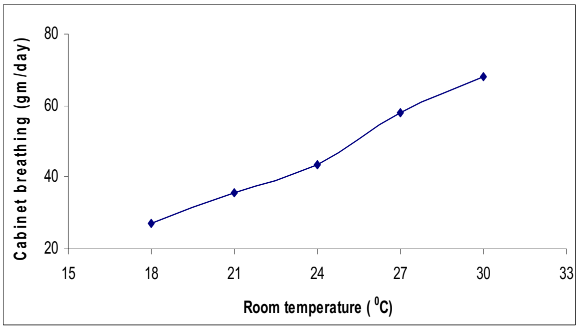

Fig. 4 Variation of cabinet breathing with ambient temperature

3.1.2 Effect of loading on moisture transfer

When the refrigerator-freezer is loaded, more thermal load is imposed. That is why the compressor operating time and the on-off frequency increase to maintain the desired temperature. The temperature fluctuation inside the cabinet is increased due to heat losses. Fig. 5 and Fig. 6 show the gasket diffusion and cabinet breathing moisture with change in the cabinet load. In the experiment, the cabinet breathing increases from 26.9 gm/day to 57.8 gm/day when the cabinet load increases from 0 kg to 12 kg. Cabinet breathing increases 2.6 gm/day for 1 kg increase in cabinet load. The effect of load on gasket diffusion moisture transfer is very small. From Fig. 5, it can be stated that there is a little influence of cabinet load on gasket diffusion moisture transfer of the refrigerator-freezer. From Fig. 6, it is found that there is a strong influence of cabinet load on cabinet breathing moisture transfer of the refrigerator-freezer.

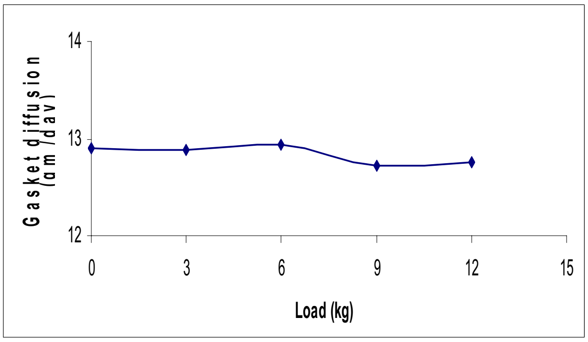

Fig. 5 Variation of gasket diffusion with load

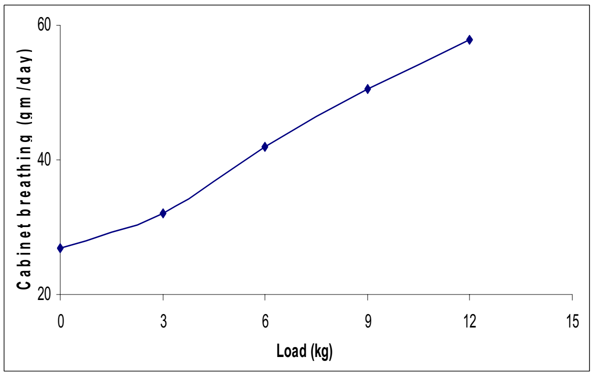

Fig. 6 Variation of cabinet breathing with load

3.1.3 Effect of thermostat setting position on moisture transfer

The function of the thermostat is to maintain the cabinet temperature by controlling the compressor operating time and on-off frequency. If refrigerator-freezer thermostat is reset in a lower (coldest) temperature, the compressor operating time and on-off frequency increase to maintain the desired temperature compare to the warmest temperature. As the on-off frequency increases, cabinet breathing increases. Fig. 7 and Fig. 8 show the gasket diffusion and cabinet breathing moisture with respect to thermostat setting position. In the investigation the cabinet breathing increases from 27.8 gm/day to 58.3 gm/day when the thermostat setting position increases from 1 (-13.1 ºC) to 5 (-17.5 ºC). On the other hand, refrigerator-freezer thermostat is reset in a lower (coldest) temperature, the temperature different increases. As temperature variation increases, gasket diffusion also increases. The gasket diffusion moisture transfer increases from 12.2 gm/day to 13.0 gm/day when the thermostat setting position increases from 1 (-13.1 ºC) to 5 (-17.5 ºC). From Fig. 7 and Fig. 8, it can be stated that there is a strong influence of thermostat setting position on moisture transfer of the refrigerator-freezer.

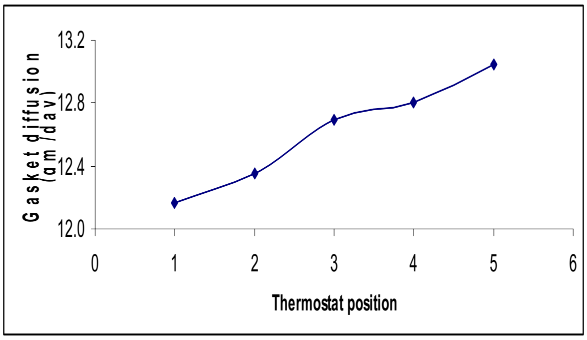

Fig. 7 Variation of gasket diffusion with thermostat setting position

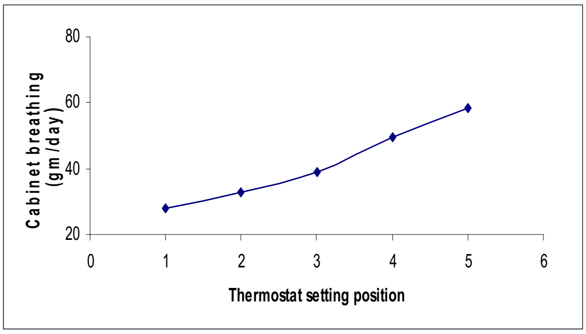

Fig. 8 Variation of cabinet breathing with thermostat setting position

3.1.4 Effect of water pan area on moisture transfer

Water evaporation rate depends on the exposed surface area of the water pan. When the open surface water pan area increases, more water is found to be evaporated from the water pan. Fig. 9 and Fig. 10 show the variations of the gasket diffusion and cabinet breathing moisture with the open surface water pan area. Cabinet breathing increases with an increasing of the open surface water pan area. The cabinet breathing increases from 27.5 gm/day to 95.1 gm/day when the open surface water pan area increased from 324 cm^2 to 1272 cm^2. Cabinet breathing increases around 7 gm/day for 100 cm^2 increase in water pan area. On the other hand, gasket diffusion remains nearly constant. From Fig. 10, it is found that there is a strong influence of open surface water pan area on cabinet breathing of the refrigerator-freezer.

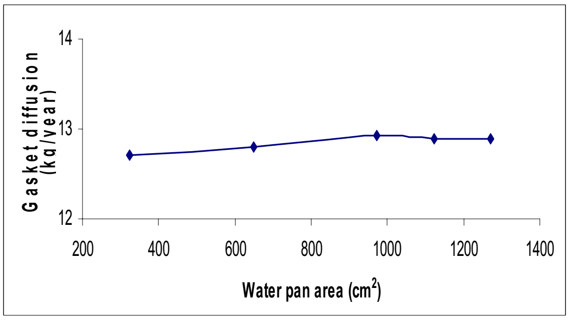

Fig. 9 Variation of gasket diffusion with water pan area

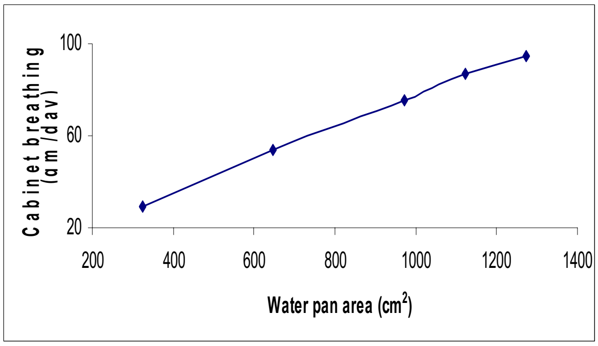

Fig. 10 Variation of cabinet breathing with water pan area

3.2 Effect of different variables on moisture transfer

Moisture transfer of the refrigerator-freezer is greatly influenced by the operating environmental condition. There is a very strong influence of ambient temperature on gasket diffusion compared to the other variables. The effect of thermostat setting position on gasket diffusion is found as minor. Gasket diffusion is all most constant during the variation of load and open surface water pan area. The overall average gasket diffusion is calculated and found as 12.7 gm/day. According to the experiment, the gasket diffusion moisture transfer is obtained at a rate of 4.6 kg/year. There is a very strong influence of open surface water pan area on cabinet breathing compared to the other variables. The influence of the ambient temperature on cabinet breathing is strong. On the other hand, the influence of the load and thermostat setting position on cabinet breathing is moderate. The overall average cabinet breathing is calculated and found as 45.1 gm/day. Here the cabinet breathing moisture transfer is found as 16.5 kg/year. Table 2 and Table 3 show the maximum, minimum and average gasket diffusion and cabinet breathing moisture transfer of the refrigerator-freezer during the closed door condition.

Table 2 Effect of different variables on gasket diffusion

Variable	Maximum (gm/day)	Minimum (gm/day)	Average (gm/day)
Ambient temperature	18.4	7.4	12.4
Load	12.9	12.9	12.9
Thermostat setting position	13.0	12.2	12.6
Water pan area	12.9	12.7	12.8

Table 3 Effect of different variables on cabinet breathing

Variable	Maximum (gm/day)	Minimum (gm/day)	Average (gm/day)
Ambient temperature	68.2	27.1	46.5
Load	57.8	26.9	41.8
Thermostat setting position	58.3	27.8	41.5
Water pan area	95.1	29.5	68.1

3.3 Energy consumption on closed door condition

The dominant purpose of utilizing household refrigerator-freezer is to keep food and vegetable fresh and to freeze the perishable food for a longer period of time in days or weeks. During the closed door condition, refrigerator-freezer consumes energy due to moisture transfer by gasket diffusion and cabinet breathing, heat transfer by conduction, convection, radiation, sensible and latent. Refrigerator-freezer consumes a significant amount of electric energy of a house continuously. Refrigerator-freezer energy consumption is influenced by the operating environmental conditions. There is a very strong influence of ambient temperature and load on energy consumption compare to the thermostat setting position and open surface water pan area. Thermostat setting position effect on energy consumption is low compared to ambient temperature and load, but there is a strong influence on energy consumption. There is a small influence of water pan area on energy consumption compared to the ambient temperature, load and thermostat setting position. The overall average energy consumption is calculated and found as 2.9 kWh/day. According to the experiment the refrigerator-freezer consumes 1043 kWh/year. Table 4 shows the maximum, minimum and average energy consumption of the refrigerator-freezer during the closed door condition.

Table 4 Effect of different variables on energy consumption

Variable	Maximum (kWh/day)	Minimum (kWh/day)	Average (kWh/day)
Ambient temperature	3.6	2.1	2.7
Load	3.5	2.2	2.8
Thermostat setting position	3.2	2.3	2.8
Water pan area	3.1	2.9	3.0

3.4 Energy loss due to moisture transfer

Malaysia, like other developing countries, has experienced dramatic growth in the use of household refrigerator-freezers. The Malaysian economy growth rate is about 7%. The Gross Domestic Product is increased from RM 572.6 billion in 2006 to RM 625.1 billion in 2007. The per capita income is increased from RM 20,841 in 2006 to RM 22,293 in 2007 (DSM, 2007). Economic growth is the main driving factor for greater use of household appliances which leads to an increasing need for comfort and a high style of living that has consequently caused a substantial increase in household energy consumption. Household refrigerator-freezer ownership increased for several reasons: (i) increase in household income, (ii) more readily available electricity, and (iii) refrigerator-freezers are more available and less expensive (Masjuki *et al.,* 2001). According to the investigation (Mahlia *et al.*, 2004), the number of refrigerator in Malaysia was about 6,258,000 units in the year of 2007. Besides, it is mentioned that there was 6,276,080 units in the year of 2007 (Saidur *et al.,* 2007). It can consider that there were 6,267,040 units in the year of 2007 in Malaysia. According to the experimental test unit, if the overall efficiency is considered as 60%, average energy loss due to moisture transfer is about 10 kWh/year. Energy loss due to moisture transfer is about 62.3 GWh/year in 2007 in Malaysia. Energy demand in Malaysia is increasing rapidly as well as increasing the greenhouse gases. Emissions of all greenhouse gases from fuel combustion activities are increasing to fulfill the energy demand. So there is a high impact on the environment as well as the global warming potential.

4 CONCLUSIONS

From the comparative evaluation of the experimental results for the different operating conditions, it is found that the different environmental operating conditions have a significant influence on the refrigerator-freezer moisture transfer and energy consumption. There is a strong influence of ambient temperature on gasket diffusion moisture transfer compared to the cabinet load, thermostat setting position and open surface water pan area. Cabinet breathing is more affected by open surface water pan area. The extra energy consumption due to the gasket diffusion and cabinet breathing moisture transfer has been obtained as 1.3 kWh/year and 4.9 kWh/year respectively. It has been also observed that the influence of ambient temperature and cabinet load on energy consumption is more dominant compared to thermostat setting position and open surface water pan area.

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