Open and Closed Door Moisture Transport and Corresponding Energy Consumption in Household Refrigerator

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Abstract

This paper presents the mode of moisture transport and their effect on energy consumption during open and closed door condition. Moisture can be transported into the refrigerator during closed and opening door conditions. Open door moisture transport depends on the number of door opening and duration of door remains open. The rate of moisture transport during open and closed door condition and energy consumption are calculated. The result of this study shows that the refrigerator with door openings consumes 8% more energy than the same refrigerator without door openings. The extra power consumption due to moisture transport during the period of 10 year by the refrigerators in Malaysia is calculated and found that 4% of the total energy is consumed.

Introduction

Refrigerators to preserve perishable foods have long been one of the essential appliances in a household. A household refrigerator is designed to maintain the freezer section at -18 ^{o}C (0 ^{o}F) and the refrigerator section at 3 ^{o}C (37 ^{o}F). Lower freezer temperatures increase energy consumption without improving the storage life of frozen foods significantly. The moisture transport plays important role to consume energy. Energy consumption depends on various factors. Moisture transport is one of the factors to consume energy. Household refrigerators consume about 90 W to 600 W of electrical energy when running in the environment at up to 43 ^{o}C (110 ^{o}F).

Several investigations on energy consumption of refrigerators have been carried out. These results indicate the complicated nature of a refrigerator cabinet that requires knowledge of several energy transport paths, refrigeration system design and user characteristics.

The previous studies [1] investigated the influence of open door conditions on a refrigerator's overall energy requirement. An examination of the details of individual factors contributing to a cabinet’s energy load has been examined [2-6].

Knackstedt [5] performed an experiment in a 0.85 m^3 refrigerator-freezer with a variety of shelf arrangements under open door conditions. The highest convective heat transfer coefficients are at the upper-front plates in the refrigerator where the warm ambient air is pulled into the cabinet and the average local heat transfer coefficients in the refrigerator range from 0.55 to 5.21 W/m$^{2.}$ Boughton [2] developed techniques for measuring the heat transfer across the gasket region of refrigerator and door edge regions. The test unit was 0.53 m^3 top-mount refrigerator and edge load was approximately 30% of total load. Laleman [6] determined that a relative humidity of 60% to 70% at typical room air temperature (20 ^{o}C to 25 ^{o}C) and fresh-food cabinet temperatures (0 to 5 ^{o}C) is the condition where latent loading begins to exceed sensible loading of a cabinet during open door conditions. Gage [3] 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 consumes 1.4 kWh/day (12% increases) more energy in 26 door opening compare to no door opening.

Alissi [1] found that open door conditions with an estimated average open door usage pattern generally account for less than 10% to 20% of a typical U.S. refrigerator's energy requirements. Energy efficiency standards have required substantial reduction in static loads, with another 30% reduction. Moisture loading effects would be 14% to 28% of the remaining cabinet load if left relatively unchanged as the 30% reduction goal is obtained.

Inan [7] 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 in a year with 20 door openings per day and extra energy consume 100 kWh/year.

Stein [8] performed to 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. Bansal and Xie [9] developed a model capable of predicting the evaporation of defrosts water drained into a pan located underneath a refrigerator cabinet. The model is capable of predicting both on-cycle and off-cycle evaporation.

Williams [4] measured local heat transfer coefficients within a refrigerator cabinet during closed door conditions. The convective heat transfer coefficient varies from 1.56 W/m^{2}K to 3.02 W/m^{2}K with an average of 2.27 W/m^{2}K. Meier and Jansky [10] investigated the field performance of refrigerator compare with the laboratory test and collected 432 refrigerators data were collected. Some technical problem and wide distribution of energy use 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

The aim of the research is to investigate the moisture transport into the refrigerator/freezer and determine the rate of moisture transport, annual moisture transport and energy consumption during open and close door conditions.

Theoretical Approaches

Moisture

Air is a mixture of gases and some extent of water vapor. But the amount of water vapor changes as a result of condensation and evaporation from oceans, lakes, rivers, showers and even the human body.

Closed door moisture transport

Gasket is used at the refrigerator-freezer door to leak prove. There are some small gaps between the gasket and cabinets / doors. Moisture is transferred from the warm ambient to the cabinets through the gaps. Refrigerator-freezer cabinets are alternately cooled and warmed up during “on/off” cycle. Inan [7] mentioned that during the “on” cycle the cabinet is cooled, air may be pulled into the fresh food compartment and in the “off” cycle the cabinet contents are warmed up and the exhaling of air may be through the freezer.

Open door moisture transport

Natural convection is occurred and the density of air is changed inside the cabinet during the door open. When the door opens, the warm and moist ambient air replaces the cool air inside the cabinet. Moist ambient air enters the cool space from the top and exits from the bottom. There are two primary time periods characterize the air exchange during a refrigerator door opening. First, a spilling or falling of the dense air from the cabinet occurs over a 5-10 second time period when a cabinet is first opened [5]. After this period, a steady flow pattern is developed. Between these two periods there is a transition period where the flow field changes from the initial spilling of the cabinet air to the steady flow pattern. The steady flow field is characterized by a large inflow area and a relatively smaller but higher velocity outflow area.

Mass transfer

It is a common observation that if there is an imbalance of a commodity in a medium, nature tends to redistribute it until a “balance” or “equality” is established. The flow rate of the commodity is proportional to the concentration gradient that is changed in the concentration per unit length in the flow direction and the area normal to flow direction. The diffusion rates will be higher at higher temperatures and molecular spacing substances. Therefore, the diffusion rates are typically much higher in gases than they are in liquids and much higher in liquids than in solids. Diffusion coefficients in gas mixtures are a few orders of magnitude larger than these of liquid or solid solutions.

Methodology

Experimental setup

Refrigerator (test unit)

The refrigerator used in this experiment was a two door refrigerator. The upper part of the refrigerator was freezer compartment where as lower part was the fresh food compartment. The technical specification is given in the Table 1.

Table 1 Technical specifications of test unit

Specifications	Value and unit
Freezer capacity	0.13 m^3
Fresh food capacity	0.33 m^3
Power rating	165 Watt
Current rating	1.3 ampere
Voltage	240 volt
Frequency	50 hertz
No. of door	2
Refrigerant type	R-134a (CF_3CH_2F)
Defrost system	Frost free

Room environment setting

The room temperature and relative humidity are controlled by the air-cooler and dehumidifier. The air-cooler controls the temperature of the chamber automatically. The desire level of humidity was set by the dehumidifier control knob. The dehumidifier controls the humidity by sensing the humidity from a humidity sensor. The experiment was conducted at a temperature of 23^{o}C and relative humidity of 80%.
Humidity sensor was used to measure the humidity of the surrounding.

Experimental procedure

Thermocouples, dehumidifier control knob and the power meter were directly connected to the data logger channels. The data logger was interfaced with the computer to store the data for future analysis.

Door opening mechanism

Automatic door opening mechanism (Fig. 1) was used to open and close the refrigerator freezer compartment automatically. The device consisted of a steel frame with AC motor and a gearbox mounted on top of it. The door closing and opening were controlled by PLC. The operation switch, which is an input device, sends signal to the motor to open and close the door.

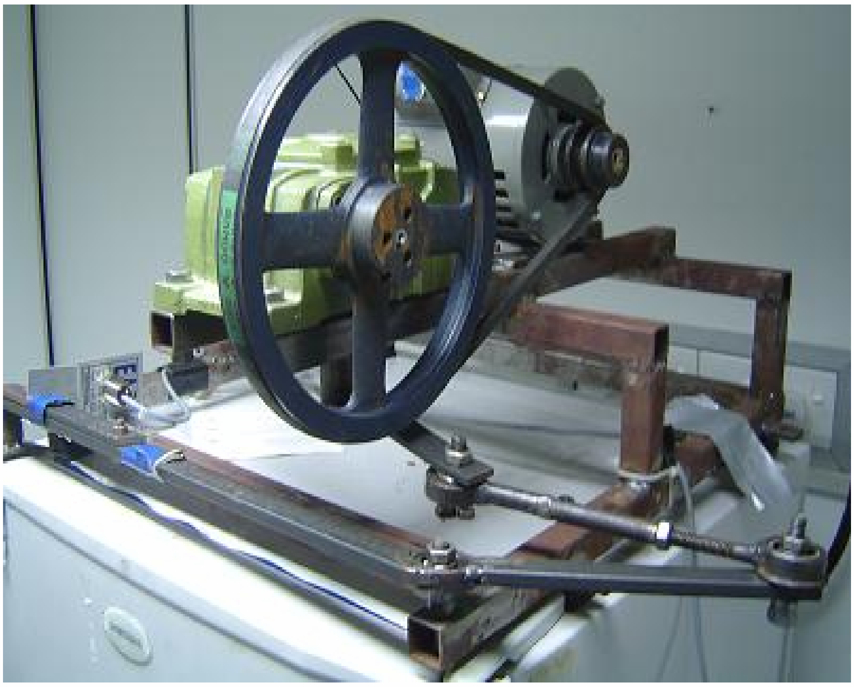

Fig. 1 Automatic door opening mechanism

Close door moisture transport

The refrigerator was operated in environmental control lab with 80% RH and 23 ^{o}C. Shallow pans of water with open surfaces and closed containers of water are added to the cabinet. The condensate water is collected through the condensate drain and weighted. The loss of water over the period of one week is determined. The fresh food compartment is loaded with water bottle to mimic the real situation. The Fig. 2 shows the pan of water placed during the closed door test. The power consumption during the closed door test was measured with the power meter.

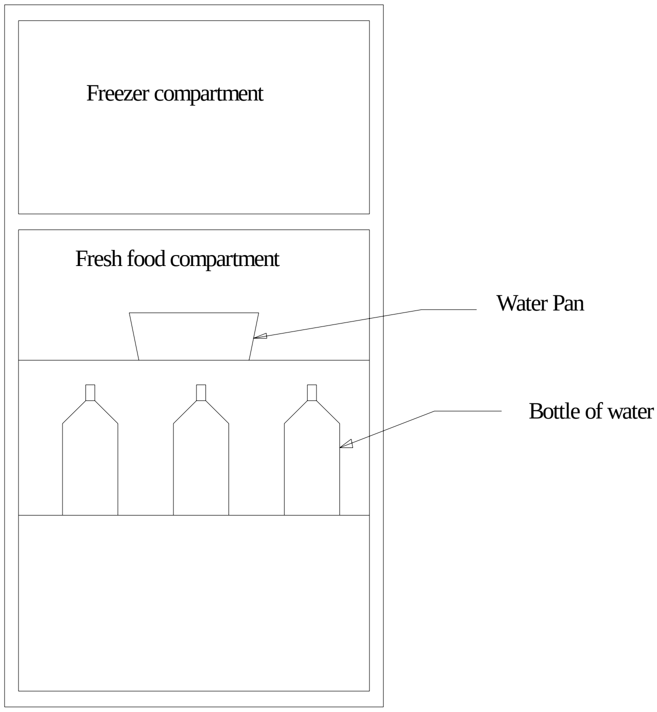

Fig. 2 Load inside the refrigerator during closed door test

Open door moisture transport

The variables of the open door moisture transport are the number of door openings, the duration of door opening, relative humidity and duration of the experiment. The door was opened at an interval of 20 minutes (3 times per hour) and the duration of each door remains open is 10 seconds. A PLC controlled automatic door opening mechanism was used to perform this job automatically. This investigation was performed with the variation of relative humidity and duration of experiment. When the door is opened it is assumed that the fresh air from the surrounding replaced the air inside the compartment. Humidity sensor was used to measure the RH of the surrounding.

Results and Discussion

Closed door moisture transport

The rate of moisture transported into the test unit during closed door condition was calculated for a period of 1 week. The water vapor transferred into the cabinet during closed door condition for 1 week is 103 g. The detailed calculation is presented in the Appendix. The rate of moisture transported into the refrigerator during closed door condition is 1.703×10^{-4} g/s. The total infiltration of water vapor into the refrigerator over the course of year is 5.36 kg. The energy required to freeze the infiltration water vapor is approximately 2820 kJ/kg. The effect of sensible cooling of water vapor, approximately 50 kJ/kg, is a negligible amount [7]. The rate of moisture transfer depends on the relative humidity of the surrounding.

Open door moisture transport

The moist air infiltration rate is 3.96×10^{-2} kg/s during open door test. The water vapor (moisture) infiltrate at a rate 0.413 g/s. Inan [7] investigated moisture transport in domestic refrigerator in the open door lasting 20 seconds, with 10 seconds of intial air exchange and 10 seconds of steady flow. The result shows that approximately 60 kg of water vapor transport in a year with 20 door openings per day. Our analysis shows that at the 20 minutes door opening duration (3 times per hour) with door remains open 10 seconds, approximately 36.18 kg of water vapor transport in a year with 24 door openings per day.

Contribution to the total energy consumption

The infiltration of the water vapor causes an extra energy 2820 kJ/kg to freeze. The refrigerator also consumes energy to cool down the air that entered into the compartment. Moreover, an extra energy is consumed by the refrigerator to cool the moisture transferred into the cabinet every time of door opening and freeze it [1]. Energy also consumed for the defrost process of the transported moisture. The extra energy consumed during the period of 1 hour due to moisture transport is 7.29 Wh. Total mass of water vapor infiltrated into the cabinet for 1 hour (3 times per hour) is12.39 g and energy consumption 0.588 Wh/g. Here it is assumed that in real situation the door was opened every 20 minutes and 8 hours a day. Energy consumption due to moisture transfer is 100 kWh/year [7]. In this experiment the total energy consumption due to the open door moisture transfer is 21.29 kWh/year. The percentage of energy consumption due to moisture transfer for all the year from 1997 to 2006 is 4%. Because of average relative humidity of year to year almost same and small of energy is consumed due to moisture transfer. So percentage of energy consumption is almost same. The total energy consumption by the refrigerator in Malaysia during the period of 1997 to 2006 is calculated and presented in the Table 2.

Table 2 Energy consumption by the refrigerators due to moisture transfer from 1997 to 2006

Year	Unit of household refrigerator	Extra power consumption due to moisture transport GWh/year	Percentage of total energy consumption due to moisture transport
1997	3,413,155	73	4
1998	3,657,439	78	4
1999	3,910,662	83	4
2000	4,196,486	89	4
2001	4,443,922	95	4
2002	4,723,959	101	4
2003	5,012,935	107	4
2004	5,310,835	113	4
2005	5,617,687	120	4
2006	5,933,476	126	4

Inan [7] found that 60 kg of water vapor per year transport into the refrigerator and this causes the refrigerator consume >100 kWh as extra load annually. From this experimental result, the water vapor transport rate is 36.18 kg/year and the energy consumption is 21.29 kWh/year. The difference for mass transfer and energy consumption is due to the fact of the difference of door opening angle, frequency of door opening, duration of door opening, volume of freezer and fresh food cabinet, relative humidity and environmental conditions.

Another is that the energy used in the defrost system to defrost the ice made up by this water vapor is not included. Refrigerator now use a timer that initiates defrost after a certain constant time span, usually around 10 to 12 hours of compressor run time [11]. However, the frost build up in a freezer can vary significantly depending on the freezer, its usage and ambient condition. If the experiment period extended for long time then the result should mimic the real situation.

Conclusion

Moisture was transported into the freezer and fresh food compartment during closed and open door conditions. During closed door moisture intrude into the freezer and fresh food compartment through the leakage of the gasket and condensation drain. There are two models of moisture transport for the closed door condition. The first one is gasket diffusion of moisture and the second one is cabinet breathing. From the result, the rate of moisture transport during closed door condition is 1.703×10^{-4} g/s. While the open door moisture transport rate is 0.413 g/s and the extra energy consumption is 21.29 kWh/year. The water vapor is transferred into the refrigerator cabinet 41.54 kg per year. The extra power consumption due to moisture transport during the period of 10 year by the refrigerators in Malaysia is 4% of the total energy consumption.

References

[1] M. A. Alissi, S. Ramadhyani and R. J. Schoenhals, "Effects of ambient temperature, ambient humidity and door openings on energy consumption of a household refrigerator-freezer", ASHRAE Transactions, Vol. 94, Part 2, pp. 1713-1735, 1988.

[2] B. E. Boughton, A. M. Clousing and T. A. Newell, "An investigation of household refrigerator cabinet loads", HVAC&R Research 2(2), pp. 135-148, 1996.

[3] C. L. Gage, "Field usage and its impact on energy consumption of refrigerator/freezers", ASHRAE Transactions, Vol. 101(2), pp. 1201-1210, 1995.

[4] T. L. Williams, A. M. Clousing and T. A. Newell, "An experimental investigation of natural convection heat transfer in a refrigerator during closed door conditions", in Proc., 46th International Appliance Technical Conference, University of Urbana-Champaign, pp. 470-481, 1995.

[5] L. N. Knackstedt, T. A. Newell and A. M. Clousing, "Heat and mass transfer in a refrigerator cabinet during open door condition", in Proc., International Appliance Technical Conference, University of Urbana-Champaign, pp 425-435, 1995.

[6] M. R. Laleman "Sensible and latent energy loading on a refrigerator during open door conditions", M. Sc. thesis, Department of Mechanical and Industrial Engineering, University of Urbana-Champaign, 1992.

[7] C. Inan, N. Egrican, C. Bullard and T. A. Newell, "Moisture transport in domestic refrigerator", ASHRAE Transaction Vol. 108, Part 1, pp. 801-806, 2002.

[8] M. A. Stein, C. Inan, C. Bullard and T. A. Newell, "Closed door moisture transport in refrigerator/freezers", International Journal of Energy Research, Vol. 26, pp. 793-805, 2002.

[9] P. K. Bansal and G. Xie, "A simulation model for evaporation of defrosted water in household refrigerators", International Journal of Refrigeration, Vol. 22, pp. 3119-3133, 1999.

[10] A. K. Meier and R. Jansky, "Field performance of residential refrigerators: a comparison with the laboratory test", ASHRAE Transactions, Vol. 99, Part 1, pp. 704-713, 1993.

[11] I. Turiel and A. Heydari, "Analysis of design options to improve the efficiency of refrigerator-freezers and Freezers", ASHRAE Transactions, Vol. 94(2), pp. 1699-1711, 1988.

Appendix

Calculation of Moisture Transfer and Energy Consumption

Closed door moisture transport

Closed door moisture transport is conducted in the environmental control chamber with 23^0 C and 80% relative humidity. The experimental data is shown in the Table 3 and calculations below.

Table 3 Mass of moisture transport for closed door experiment

Measurement	Mass (g)
Initial mass of one pan water (including the pan itself)	177
Total of initial mass of pan water, m_{pw0} = 3 x 117g	530
Final mass of one pan water	125
Total of final mass of pan water, m_{pw1} = 3 x 125g	375
Initial mass of defrosted water container (empty)	12
Final mass of defrosted water container (with defrosted water)	270
Mass of defrosted water, m_{dw} = 270g – 12g	258

The water vapor evaporated from the pan water

$$\Delta m_{pw} = m_{pw0} - m_{pw1} \tag{1}$$

where,
m_{pw0} =530 g (Total of initial mass of pan water)
m_{pw1} =375 g (Total of final mass of pan water)

Based on the parameter and using Equation 1, the water vapor evaporated from the pan water 155g. The water vapor transferred into the cabinet in during closed door condition for 1 week experiment time can get from subtracting the mass of pan evaporation water vapor from the mass of defrosted water.

$$m_w = m_{dw} - \Delta m_{pw} \tag{2}$$

where,
m_{dw} =258 g (Mass of defrosted water)

By using Equation 2, the water vapor transferred into the cabinet in during closed door condition for 1 week experiment is 103 g. The rate of moisture transported into the refrigerator during closed door condition,

$$\dot{m}_w = \frac{m_w}{24x60x60x7} \tag{3}$$

$$= \frac{103g}{60,4800s}$$

$$= 1.703 \text{ x } 10^{-4} \text{ g/s}$$

The mass of water vapor transferred due to closed door condition in one year:

$M_{water,closed}$ = $(1.703 \times 10^{-4}) \times (3600 \times 24 \times 365 - 10\times3\times8\times365)$ g/year
=5356 g/year
= 5.36 kg / year

Open door moisture transport

Open door moisture transport is conducted in the environmental control chamber. The experimental data is shown in the Table 4 and calculations below.

Table 4 Relative humidity and temperatures for open door experiment

	Initial Opening	RH(%)		T room (°C)	T fresh food (°C)	Energy Consumption (Wh)
		Room	Refrigerator			
Test 1	1st	80	32	23	12	89
	2nd	83	32	23	12	
	3rd	82	55	23	13	
Test 2	1st	85	24	23	12	87
	2nd	86	36	23	12	
	3rd	87	53	23	13	
Test 3	1st	81	26	23	13	100
	2nd	80	65	23	14	
	3rd	82	70	23	16	
Test 4	1st	83	30	23	15	100
	2nd	84	61	23	14	
	3rd	81	55	23	15	
Average		83	45	23	13	94

T fresh food is the average temperature taken at 3 different shelves locations inside the cabinet.

During open door condition, the dry air transfer rate is given by the Equation 4.

$$\dot{m}_{air} = \frac{\rho_a v_{cab}}{\Delta t_{init}} \quad (4)$$

where,
V_{cab} = cabinet volume = 0.330 m^3
ρ_a = air density = 1.2 kg /m^3
Δt_{init} = assumed initial time period = 10 seconds

The parameters are substituted into the above equation, the air transfer rate 0.0396 kg/s. When the doors open the ambient moisture air replaces the cabinet. The water vapor transfer rate is calculated by the Equation 5.

$$\dot{m}_{water} = \dot{m}_{air}(\omega_{room} - \omega_{cabinet}) \quad (5)$$

where,

ω_{room} =room air humidity ratio

$\omega_{cabinet}$ =cabinet air humidity ratio

By substituting the humidity ratio into Equation 5, the water vapor transfer rate 0.413 g/s. Total mass of water vapor transferred into the cabinet for 1 hour (3 times door opening) is:

$$m_{water} = 3\times \dot{m}_{water} \times 10 \text{ sec}$$
$$= 3 \times 0.413 \text{ g/s} \times 10 \text{ s}$$
$$= 12.39 \text{ g}$$

The total mass of water vapor transferred in one year during open door is:

$$M_{water} = 12.39\text{g} \times 8 \times 365$$
$$= 36.18 \text{ kg / year}$$

Energy consumption

The power consumption of experiment is investigated. The power consumption are measured both in the open and closed door condition using the power meter and presented in Table 5.

Table 5 Average energy consumption for open and closed door experiment

Experiment Type	Temperature (°C)	Total Run Time (minutes)	Energy Consumption (Wh)
Open Door	23	60	94.09
Closed Door	23	60	86.80

The closed door energy consumption is the 1 hour average value for the 4 hours total run time.

The extra energy consumption by the moisture transported in 1 hour,

$$E = (94.09 – 86.80) \text{ Wh}$$
$$= 7.29 \text{ Wh}$$

Energy consumption of 1 g of water vapor = $\frac{7.29}{12.39}$ Wh/g

= 0.588 Wh/g

Assuming in real situation the door was opened every 20 minutes (3 times per hour) and 8 hours a day. The total energy consumption due to the moisture transfer during opening door in a year is:

$$E = (7.29 \times 8 \times 365) \text{ kWh}$$
$$= 21.29 \text{ kWh / year}$$