Journal of Mechanical Engineering and Automation 2015, 5(1): 20-28
DOI: 10.5923/j.jmea.20150501.03

Effect of Evaporator Heater Power Input and Refrigerant Flow Rate on the Performance of a Refrigerator – Developing Empirical Models

Ali Naif*, Abdulkareem Shafiq Mahdi Al-Obaidi, Mohammad H. Nassir

School of Engineering, Taylor’s University, Malaysia

Abstract Refrigerators normally are systems that are used to preserve perishable goods in a house hold by reducing the temperature of the food compartments. However, refrigerators are also infamous for their high electricity consumptions. This paper presents first a comparison between theoretical and experimental determination of the tons of refrigeration (TR) of a vapor compression refrigeration cycle (VCRC). Then, it was looked into the derivation of empirical models, grounded on experimental results, which would provide refrigerator designers a reliable mean to check on the impact of each examined parameter on the TR during the preliminary stage of refrigerator design. It was noted that both evaporator heater power input (EHPI) and refrigerant flow rate (RFR) positively affected the tons of refrigeration, while the effects of condenser water flow rate (CWFR) was negligible. A total of three models generated. As the accuracy of the data for all models were about 99.7%, the minute difference had to be looked in to. Hence, Model 1, considering both evaporator heater power input (EHPI) and refrigerant flow rate (RFR), produced a lower range of error compared to model 2 and 3. This indicated that Model 1 was the best predictor of TR. The outcomes of the final model were within the uncertainty range of 4.82% and-3.14% compared to the experimental results. This was with in the acceptable range of ±10%. The overall model could be enhance by incorporating other significant evaporator side parameter as independent parameter.

Keywords Coefficient of Performance, Refrigeration, Efficiency, Vapor Compression Cycle, Empirical model

1. Introduction

1.1. Background

A Household refrigerator is a commonly used electrical appliance which has a soul purpose of preserving perishable good, most commonly food, by dropping the temperature of its storage compartments. Amongst many types of refrigeration cycles, vapor compression refrigeration cycles (VCRC) are the most broadly used cycle for household refrigerators due to its high flexibility. Despite the importance, refrigerators are known for their high energy consumption alongside air conditioning systems. This is mainly because of the around the clock operation and the complexity of the individual mechanical and electrical components with in the refrigerator. Therefore, it has become a necessity to optimize the performance of a refrigerator so that the global energy consumption could also be positively impacted.

During the past few decades, many different physical modifications and hybridizations has be brought to the VCRC in efforts to improve the performance of the refrigerator. Amongst these modifications, one of the most commonly studied type of modification is ejector-vapor compression cycles (EVCC). Yan et al. [1] used R134a as the working fluid and was able to improve the performance of the EVCC refrigerators by14.5%. Similarly, Ersoy & Bilir Sag [2] used numerous different types of working fluids to improve the overall performance of the EVCC by 21%. Wang et al. [3] utilized organic Rankine cycle (ORC) to hybridize the basic VCRC and increased the performance although not as much as EVCC systems. Furthermore, Molés et al. [4] also studies a single stage hybrid VCRC using non-conventional refrigerants and found that the overall performance increased by to 15% and 20% while the performance of the basic VCRC reduced by 4% to 8% using the same refrigerants. Although, the hybrid cycle was improved it was also indicated that replacement of conventional refrigerants may increase the complexity of the practicality of the system and ultimately the cost.

Based on the studies, it was noted that although the system may be allowed to improve its performance, there always was a compensation in terms of cost. Normally, hybridized system contains more than double the number component as compared to the VCRC. Hence, the overall energy intake to

* Corresponding author:
alinaif01@gmail.com (Ali Naif)
Published online at http://journal.sapub.org/jmea

the system also would increase in order to facilitate for the increased number of components. Therefore, in most cases, the level of optimization accomplished by a method of hybridizing a simple system may be relatively low as compared to the effort and money put into the hybridization alone. Moreover, Sarkar [5] indicated that, besides encouraging progress, further research and development was required to make an impact in large scale usage. This, along with high market prices dues to modifications, may be the reason why these technologies are either not available or too expensive in the market.

Therefore, in order to reduce the cost of research and production, optimizations by mathematical or empirical modeling based on theoretical or experimental data is a viable alternative to extensive modifications. It is also a cheap and ideal field of preliminary optimizations worth probing in to, as to make efficient refrigerators more affordable to a larger portion of the consumers. This in turn would also reduce the global energy consumption as a whole.

So, capturing the opportunity, mathematical models were probed by Domanski et al., Gonçalves et al., Wallace et al., Wainaina et al and Zhao et al. [6-10], and delivered perceptiveoutcomes that were related to low cost optimization of the basic VCRC. Likewise, Jain et al., Getu & Bansal, Li & Alleyne, Navarro-Esbríet al. and Waltrich et al. [11-15] also formedmodel that would optimize the VCRC. However, as these studies utilized complez algorithms, the simplisity absent as it may be compare to a linear regression model.

Yusof & Azizuddin [16] conducted a study to determine how different operational and performance parameters of a simple household refrigerator varied over time. Although, a direct correlations of the operational and performance parameters were not concluded, the reseach methodology and technique provided insightful information about the operational and performance parameters. Amongst the important parameters of a refrigerator, refrigerant chage or refrigerant flow rate was found to have a sigificant amount of positive effect on the overall performance of the refrigerator as studied by Zhang et al., Kim & Braun, Chae & Choi [17-19]. Moreover, Boeng & Melo [20] argued that despite the positive effect of the refrigerant flow on a performance of a refrigerator, it may also reduce the performance by about 30% corresponding to the performance of other components in the system.

In efforts to design optimally performing refrigerators, the determinations of the effects of operational parameters on the performance parameters during the preliminary design stage is imperative. Also, to make the efficient systems more affordable, the ideal method of finding the parameter correlations is through a mathematical based models as they are relatively cheap, convenient and yet reliable. Model based optimizations also consists the flexibility of determining the importance of the design parameters in a system that is already available. Therefore, optimization of the simple VCRC could provide priceless and insightful information which could be used during the preliminary design stage of household refrigerator systems. With such optimized models, a VCRC refrigeration systems could be design to have optimal efficiency with low initial cost and almost negligible amount of testing.

Hence, the aim of this paper is to develop empirical models that correlates the effects of evaporator heater power input (EHPI) and R134a refrigerant flow rate (RFR) with the refrigeration capacity in tons of refrigeration (TR)of the vapor compression refrigeration cycle (VCRC), and ultimately fabricating a quick, cheap and yet reliably accurate tool during the preliminary design stage.

1.2. Tons of Refrigeration

A Ton of Refrigeration (TR) refers to the amount of ice, in tons, that could be melt by the equivalent amount of heat energy absorbed by the low pressure end of a refrigerator in 24 hours. Among the different criteria of performance of a refrigerator, TR is more commonly used in the refrigeration industries. Theoretical equations for TR is shows in Eq. 1.

$$TR = \frac{\dot{m}_r \times \Delta h_E}{3.516} = \frac{\dot{m}_r \times (h_1 - h_4)}{3.516} \quad (1)$$

The rate of heat transfer is the product of the refrigerant charge or flow rate, $\dot{m}_r$, and the enthalpy difference across the evaporator, Δh_E. Generally, a Ton is equivalent to 3.516 kW. Hence, dividing the rate of heat flow by 3.516 kW provides the results in Tons.

Generally, the performance of the refrigerator may vary over time due to performance and operational conditions. Fluctuation of the performance may rise due to opening and closing of the refrigerator door and also introduction of food. Refrigerators may be made to perform exceptionally better by modifying and altering its elements. But, extensive modifications and experimentations usually result in a high cost as they may require state of the art components and research.

2. Methodology

2.1. Refrigerant Cycle

Vapor compression refrigeration cycles (VCRC) are one of the common and flexible refrigeration cycle. VCRCs are appropriate for a wide range of uses from watts to a few megawatts. A VCRC consists of a compressor, condenser, expansion device, evaporator and a working fluid; a refrigerant as seen in Fig. 1.

The state of the working fluid, is significantly changed across the four components. Similarly, at each state noted from 1 to 4 in Fig. 1, the working fluid acquires a different physical states or characteristics. The operations of the components from one state to another with in the cycle are describes as:

- 1 to 2 Compression of superheated vapor
- 2 to 3 Condensation of superheated vapor to saturated liquid
- 3 to 4 Expansion of saturated liquid to mixture

– 4 to 1 Evaporation of mixture to superheated vapor

During State 1, the temperature and pressure of the working fluid is the highest. Then, at State 2 the temperature is significantly lowered due to the heat released to the heat sink across the condenser while the high pressure is maintained. During State 3, the temperature and the pressure of the working fluid is the lowest due to the expansion proves across the expansion valve. Lastly, at State 4, the temperature is significantly increased due to the absorption of heat from the heat source across the evaporator while comparatively low pressure is sustained.

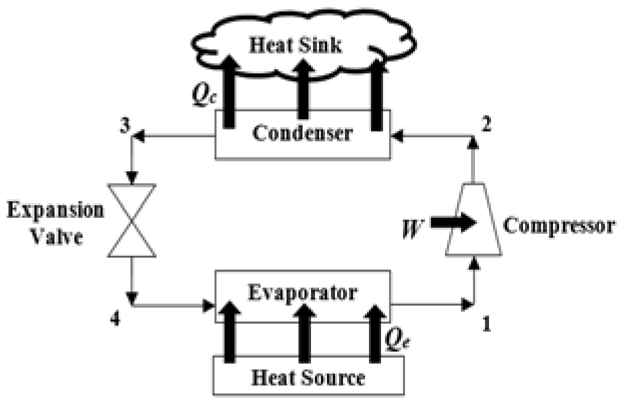

Figure 1. Simple Vapor Compression Refrigeration Cycle

Analyzing ideal VCRC may provide crucial information about the full potential. However, it would indisputably be an overestimation of the performance of a real life refrigeration systems as the irreversibility is not considered. But, a comparison between the ideal and actual VCRC would help identify the uncertainties in real operations.

2.2. Parameter Selection, Experimental Setup and Assumptions

In order to attain data for this study, the experimentations were performed using R713 Refrigeration Laboratory Unit by P.A. Hilton Ltd, as seen in Fig. 2. The experimentation rig was explicitly designed to study the performance of the refrigeration cycle. However, the only controllable parameters for this rig was evaporator heater voltage (EHV), and the condenser water flow rate (CWFR). The refrigerant charge or flow rate (RFR) and the evaporator heater current (EVI) was adjusted automatically to produce the operational conditions. In addition to the limitation of the experimental apparatus, the project duration was also a major deciding factor of the independent and dependent variable for the study. Tons of refrigeration (TR) was chosen as the dependent variable, while evaporator heater power input (EHPI) and the refrigerant charge (RFR) were chosen as the independent variable. Supportively, by definition, the dependent variable is only concerned about the performance of low pressure end of the VCRC which further indicates that the inclusion of EHPI and RFR in the model is necessary. Moreover, a study conducted by Al-Rashed [21] overlooked the effect of evaporator on the performance. It was also noted the effect of the evaporator performance influenced the overall performance of the refrigeration cycle.

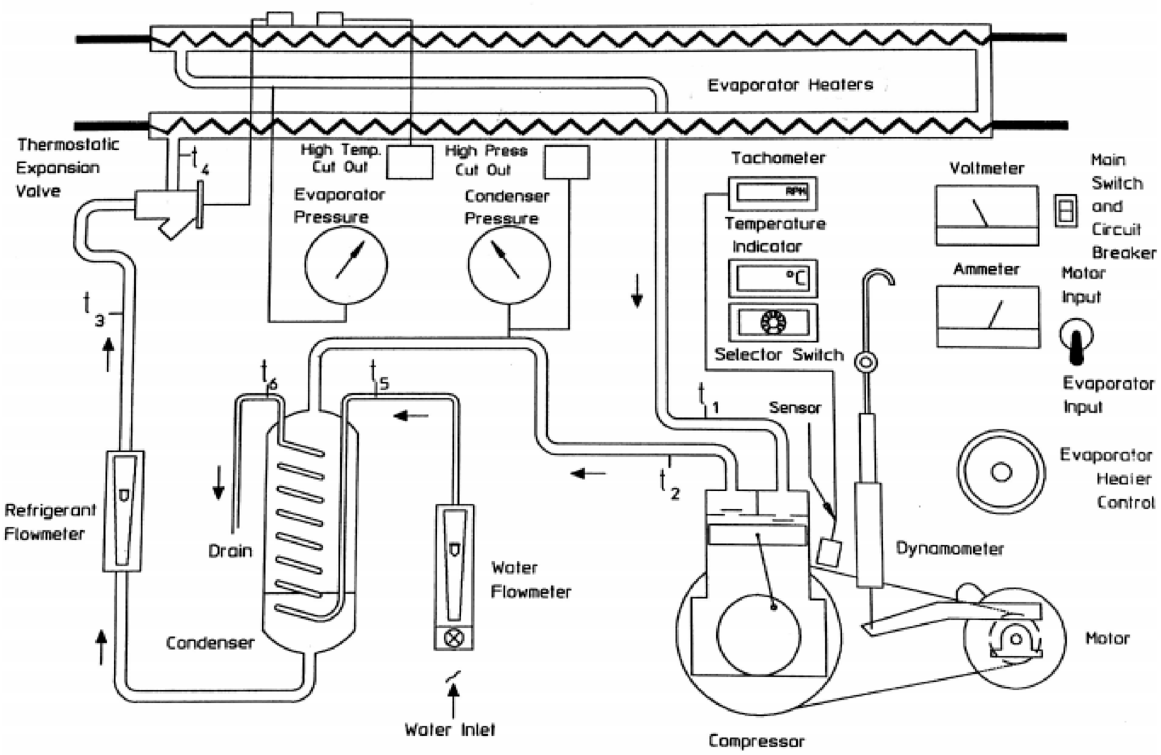

Figure 2. R713 Refrigeration Laboratory Unit – Experimentation Apparatus [22]

Despite the overall control of the operational parameters were limited, R713 Laboratory Unit was the ideal set up to study the heat flow rate at the evaporator end in more focused and isolative manner compared to a household refrigerator. Otherwise, a household refrigerator may require precise installations of sensors, gauges and displays to carefully monitor and control parameters making the system more susceptible to error. Also, it was noted by Yusof & Azizuddin, that the COP of a household refrigerator may be effected even with a minor change such as opening the door or wind velocity [16]. Therefore, R713 Refrigeration unit was ideal for the experimentations in efforts to create an optimized empirical model which would predict the TR of the VCRC based on the EHPI and RFR.

In the case of R713 Refrigeration Unit, the heat sources were two separate electrical heating elements that was controlled by a common dial gauge controller. The heat sink was flowing water which was controlled by a valve in the flowmeter. State 5 and 6 indicated the water inlet and outlet conditions respectively.

Moreover, the study was conducted using HFC134a, also known as R134a. According to Qureshi & Zubair [23], R134a was ideal for small to medium scale applications. R134a is also a very widely used refrigerant in the industry because of its low Ozone Depletion Potential (OPD) and Global Warming Potential (GWP).

Furthermore, in order to segregate the performance of the EHPI and RFR, and facilitate the short duration of the study, the cycle was simplified and the following assumptions were made:

- Atmospheric temperature, pressure and humidity was set as 27 ℃, 100kPa and 75% respectively.
- The system runs in steady state.
- Kinetic and potential energy as well as friction losses are considered to be negligible.
- Evaporator, Expansion valve, Condenser and Compressor are considered adiabatic.
- The expansion valve process is isenthalpic (constant enthalpy).
- The working fluid at the evaporator outlet is completely saturated vapor.
- The working fluid at the condenser outlet is completely saturated liquid.
- Pressure drop across the evaporator and condenser are negligible.
- All heat exchange processes were through Copper tubing or constant thermal coefficient of the medium.

Experiments were conducted for 20 g/s, 30 g/s, 40 g/s and 50 g/s CWFR, from the possible minimum to maximum evaporator heater voltage input in increments of 10V. Each system was allowed to run for about 10 minute in order to stabilize and provide a constant reading for each measure. The EHPI was found based on the auto generated evaporator hear current (EHI). The minimum EHPI value was determined by observing the lowest EHPI that resulted the least positive evaporator pressure. Similarly, the highest EHPI was found to be the last EHPI that provided uninterrupted operation before automatic system shut-off.

2.3. Multiple Linear Regression Analysis

As a simple, yet well-established statistical analysis method, multiple linear regression (MLR) analysis was used to explore the relationship between the multiple independent variables and the dependent variables and ultimately producing the empirical models. As MLR analysis was manually impractical, the data collected for this study was processed with “IBM SPSS Statistic 20” software, which was a software specialized in statistical analysis [24]. The expected outcome for this study is a mathematical model in the form of a linear equation as shown in Eq. 2. Additionally, C_1, C_2 and C_3would be coefficients for the mathematical TR model.

$$TR = C_1(EHPI) + C_2(RFR) + C_3 \qquad (2)$$

3. Results and Discussions

In order to evaluate the tons of refrigeration (TR), the enthalpy for each state of experimental data was analyzed with respect to maximum evaporator and condenser pressures using the thermodynamic property tables for the refrigerant R134a. Based on the data obtained, it was noticed that the refrigerant flow rate (RFR) was similar for each evaporator heater power input (EHPI) despite the change condenser water flow rate (CWFR). In fact, the difference between the RFR for the same EHPI was small, the RFR could be averaged as seen in Table 3. It was observed that the RFR increase linearly with the EHPI. Therefore, data was tabulated based on the average RFR and the optimized formula for VCRC was produced through MLR analysis.

Concluding the behavior of the average RFR in regards to the changes in EHPI, it was known that the RFR increase by 6.164 g/s on average for every increment of 1 kW in EHPI.

3.1. Evaporator Heater Power Input

Evaporator is the component of the refrigerator which absorbs heat energy in to the refrigeration cycle and vaporize the working fluid. In this study, evaporator heater power (EHPI) acts as the heat source for the refrigeration cycle. As the average refrigerant flow rate (RFR) behaved directly proportional to the EHPI, the behavior of tons of refrigerant (TR) would be identical for both EHPI and RFR. Evaporator heater power input was measured in watts (W).

The effect of the EHPI on the TR was illustrated in Fig. 4. Based on the observation, the well distributed manner at which the data was packed along the, almost overlapping, best-fit-lines indicated that the effect of EHPI was directly proportional to the TR at all condenser water flow rates (CWFR).

The gradients of the regression lines for all CWFRs were roughly about 0.0002 Tons/W with negligible amount of variation. The behavior of the graph indicates that the CWFR does not have a significant affect the TR, while for EHPI the effect was significant. This was simply because TR is a measure of efficiency that solely focuses on the evaporator end. CWFR as the heat sink is irrelevant at the evaporator side and only considerable at the condenser side. The gradient of the plots for all CWFR would have been extremely close if relevant data was available for the most extreme high and lower EHPI and lower CWFR. This has been observed at EHPI values below 600 W. Nevertheless, these trends could be utilized to predict the TR for a known set of EHPI, CWFR and TR.

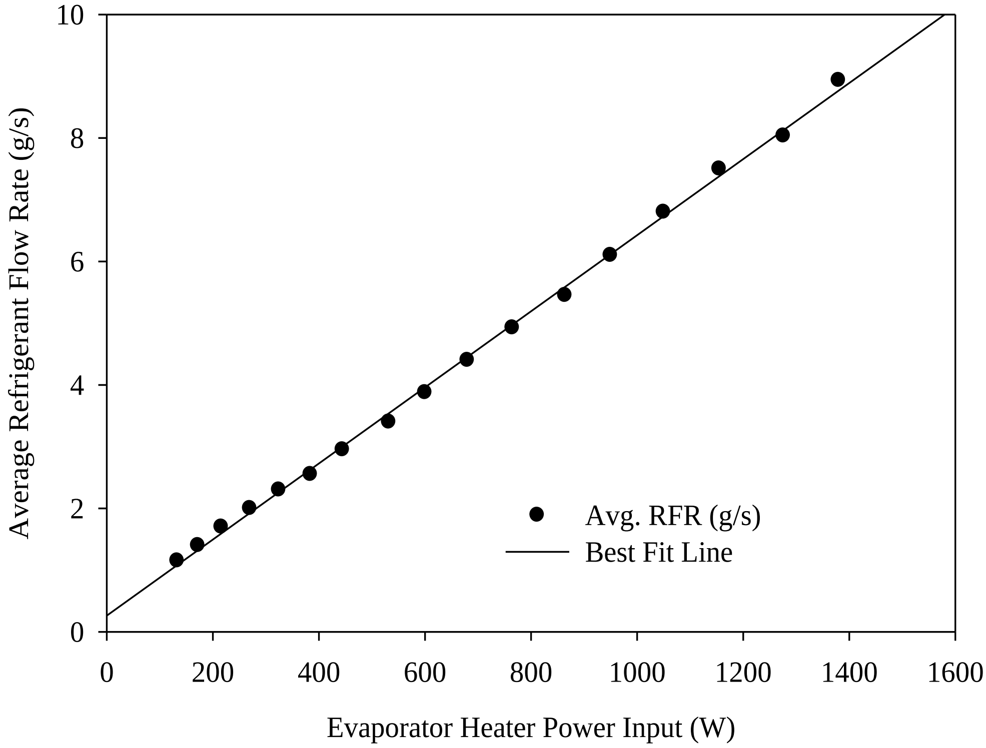

Figure 3. Effects of Evaporator Heater Power Input on the Refrigerant Flow Rate

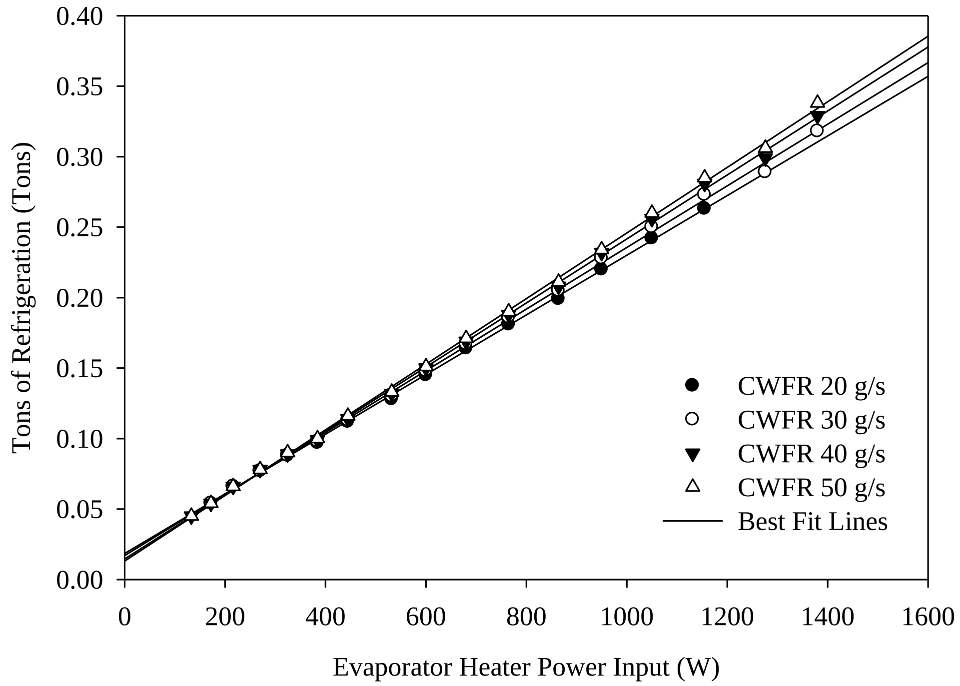

Figure 4. Effects of Evaporator Heater Power Input on the Tons of Refrigeration

3.2. Refrigerant Flow Rate

Refrigerant is the medium of heat transportation used with in a refrigeration cycle. Generally, low temperature refrigerant would absorb heat from the evaporator side and extract the heat to the surrounding at the condenser side. Refrigerant generally have low melding and boiling points to aid heat transfer process with a heat pump. Refrigerant flow rate was measured in grams per second (g/s).

Similarly, the effect of the RFR on the TR was demonstrated in Fig. 5. Based on the observation, the pattern of the plots were identical to the EHPI plots. This was unsurprising because of the previously mentioned proportionality between these two parameter. Likewise the EHPI, the data is distributed well along the best-fit-lines indicating that the effect of RFR was also directly proportional to the TR at all condenser water flow rates (CWFR).

The gradients of the regression lines for all CWFRs were roughly about 0.0405Tons/gs^{-1}. Similar to EHPI behavior, the amount a gradient variance was negligible. Yet again, the effect CWFR was found to be insignificant on the TR. However alike EHPI, the effects of RFR was significant and in fact almost 20 times more than EHPI. This difference in significance could be reaffirmed by investigating the significance of RFR as $\dot{m}_r$, in Eq. 1. Furthermore, the gradient of RFR plots for all CWFR would have been identical provided that applicable data was accessible for the extreme high and lower RFR and lower CWFR just like the in the EHPI plot. This has been observed at RFR values below 4 g/s. Hence, this trends could also be utilized to predict the TR for a known set of EHPI, CWFR and TR.

3.3. Condenser Water Flow Rate

Condenser is the element of the refrigerator at which heat energy is removed from the refrigeration cycle and liquefy the working fluid. In this analysis, condenser water flow rate (CWFR) would be the heat sink of the refrigeration cycle. Condenser water flow rate was measured in grams per second (g/s).

It is important that all independent variables were evaluated individually in order to investigate which variable contributed the most to the TR. Therefore, the effect of the CWFR on the TR was demonstrated in Fig. 6. Based on the observation, unlike EHPI and TR, the pattern of the plots were somewhat flat for low EHPI or RFR indicated that there was now effect on the TR. However for higher EHPI or RFR, a small amount of increment in tons of refrigeration was observed. This increment was noticeable at EHPI or RFR values higher than 384 W or 2.55 g/s respectively. Therefore, it was notable that CWFR had an insignificantly low effect, on the TR.

3.4. Multiple Linear Regression Analysis

Based on the result, it was clear that the evaporator heater power input (EHPI) and refrigerant flow rate (RFR) has a significantly positive effect on the tons of refrigeration (TR). However, it was also noted that condenser water flow rate (CWFR) had a negligible amount of effect on the compared to the effects of EHPI and RFR. Hence, CWFR will not be included in this model.

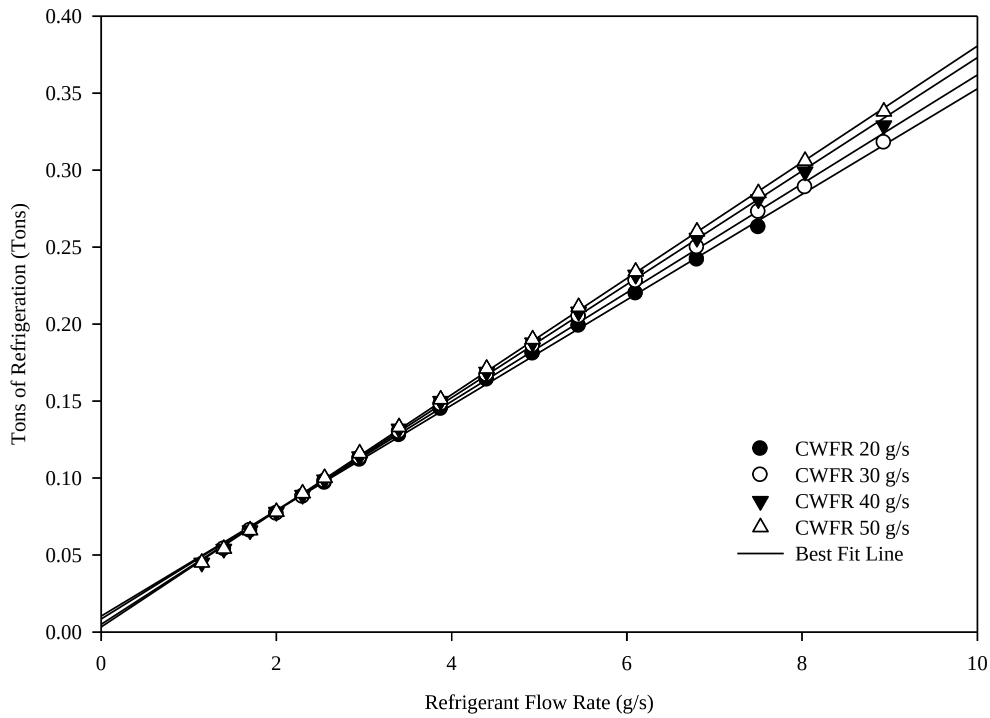

Figure 5. Effects of Evaporator Heater Power Input on the Tons of Refrigeration

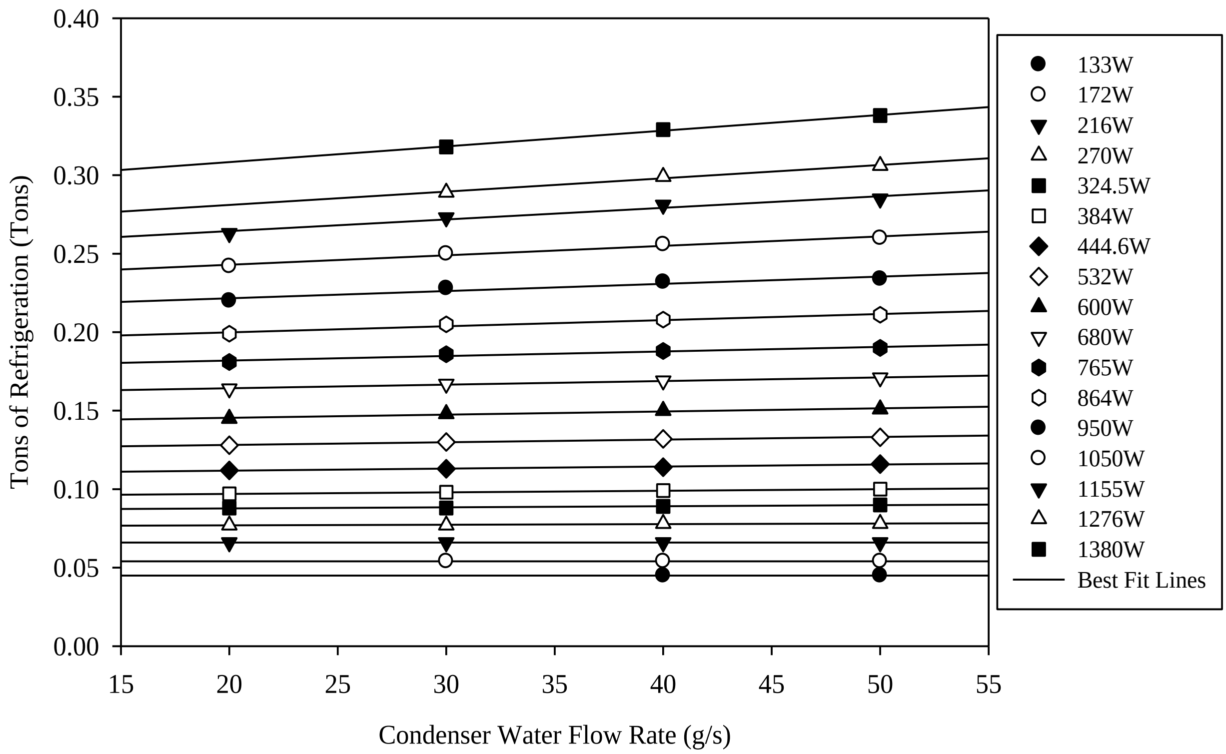

Figure 6. Effects of Condenser Water Flow Rate on the Tons of Refrigeration

Performing a multiple linear regression analysis manually would consume a huge amount of time and tends to have higher error. However, as the anticipated product of this study was to develop mathematical models in the form of a linear equations that could predict the performance based on predetermined independent variable, a statistical software was used to perform the analysis through simulation. The software used to generate the results was "IBM SPSS statistics 20". Hence, the obtained TR results were input to the software in regards to the EHPI and RFR.

Descriptive statistics produced by the MLR simulations as seen in Table 1, indicates that the mean TR of the system was 0.1633 Tons with a standard deviation of 0.0833 Tons. Likewise, EHPI and RFR had mean values of 661.81 W and 4.34g/s respectively, while the standard deviations were 370.61W and 2.29 g/s respectively. Therefore, the average TR of this refrigeration unit may vary between 0.247 W and 0.08 W. Similarly, the EHPI may vary between 291.2W and 1032.4W, while the RFR may vary between 25.03g/s and 47.03g/s.

Table 1. Descriptive Statistics

Variables	Mean	Standard Deviations
TR	0.1633	0.0833
EHPI (W)	661.81	370.61
RFR (g/s)	4.34	2.29

In Table 2, R-squared and adjusted R-squared values are shown. R-square, or coefficient of multiple determination in multiple regression, is the statistical measure of accuracy of the data fitted into regression lines. Therefore, the closer the value of R-square is to the value 1, the more accurate the data of the model would be. A total of three model were generated. Model 1 considered both EHPI and CWFR as independent variable, while Model 2 and Model 3 only considered EHPI and CWFR respectively. Hence, as seen in Table 2, all three models produced have the same amount of accuracy in terms of data distribution about the best fit line.

Table 2. Model Summary

Models	R-square	Adjusted R-square
1	0.997	0.997
2	0.997	0.997
3	0.997	0.997

Moreover, because the number of data used in the study is relatively small, the results may be overestimated. Hence, the adjusted R-square is also produced. In this case, both the R-squared and adjusted R-square are same. This indicates that the final results that will be produced would be 99.7% accurate, given that the same parameters are taken in to account in the calculations. Therefore, two sets of coefficients based on the beta level of the data was produced. The two sets of coefficients produced are known as the unstandardized and standardized coefficients as seen in Table 3.

Table 3. Unstandardized and Standardized Beta Coefficients

Models		Unstandardized Coefficients, B	Standardized coefficient, β
1	Constant	0.009515	-
	EHPI	0.000097	0.432153
	RFR	0.020636	0.566686
2	Constant	0.014738	-
	EHPI	0.000225	0.998381
3	Constant	0.005638	-
	RFR	0.036361	0.998490

The main difference between the standardized and unstandardized coefficients is that the, unlike the unstandardized coefficient, standardized coefficients for each of the variable is converted to the same scale so that a constant would not be required. The removal of the constant in standardized coefficients would also lower the accuracy of the model compare to the unstandardized models. Thus, ideally, the unstandardized coefficients would be the more reliable set of coefficients for the model to predict the performance. In relations with the behavior of R-square and adjusted R-square, standardized and unstandardized coefficients and, the number of parameters taken in to account, the most reliable model was Model 1. Therefore, replacing the coefficients C_1, C_2 and C_3 in Eq. (3), Model 1 would be presented as:

$$TR_1 = \frac{0.097(EHPI)+20.63(RFR)+9.515}{1000} \quad (3)$$

Table 4. Error Analysis

Evaporator Heater Power Input	Condenser Water Flow rate			
	20 g/s	30 g/s	40 g/s	50 g/s
133	-	-	2.49	2.49
172	-	1.98	1.98	1.98
216	-0.69	-0.69	-0.69	-0.69
270	-0.03	-0.03	-1.33	-1.33
324.5	0.51	0.51	-0.62	-1.75
384	2.40	1.39	0.39	-0.62
444.6	1.34	0.46	-0.43	-2.19
532	2.50	0.98	-0.55	-1.31
600	1.81	-0.22	-1.57	-2.25
680	1.37	-0.44	-1.64	-2.84
765	2.35	-0.35	-1.43	-2.51
864	3.30	0.38	-1.07	-2.53
950	3.32	-0.20	-1.96	-2.84
1050	3.85	0.67	-1.71	-3.30
1155	4.82	1.20	-1.69	-3.14
1276	-	3.36	0.02	-2.32
1380	-	2.97	-0.39	-3.14

A comparison between the tons of refrigeration achieved experimentally and by the obtained model was made. It was noticed that results produced by the model had a bigger error compared to the experimental values when the CWFR was low, as seen in Table 4. The highest error was 4.82% when the EHPI or RFR was the highest and CWFR was the lowest. For the overall performance of the system, the errors ranged from 4.82% to -3.14%.

The polarity of the error indicates whether the model underestimated or overestimated the results compared to experimental results. But, the model also achieved results that was only 0.02% uncertainty showing its integrity. Nonetheless, the errors produced by the model was within the expected range of ±10%. The error could be minimized even further by including more effective, yet varying, parameter such as refrigerant flow rate and also by further limiting the losses.

4. Conclusions

In conclusion, it was noted that both evaporator heater power input (EHPI) and refrigerant flow rate (RFR) positively affected the tons of refrigeration, while the effects of condenser water flow rate (CWFR) was negligible. The error in terms of the closeness of the data to the best fit line, did differ much for the three models generated.

– Amongst 3 generated mathematical models, Model 1, taking both EHPI and RFR in to consideration, was found to be the best predictor of TR using unstandardized coefficients.
– The linear regression model produced was $TR_1 = \frac{0.097(EHPI)+20.63(RFR)+9.515}{1000}$.
– The results produced by this model was within the rage of 4.82 and -3.14% with errors as low as 0.02%.
– The overall model could be enhance by incorporating other significant parameter such as heat exchanger surface area, refrigerant properties and also the evaporator inlet and outlet temperatures as independent parameter.

REFERENCES

[1] J. Yan, W. Cai, L. Zhao, Y. Li, and C. Lin, "Performance evaluation of a combined ejector-vapor compression cycle," *Renew. Energy*, vol. 55, pp. 331–337, Jul. 2013.

[2] H. K. Ersoy and N. Bilir Sag, "Preliminary experimental results on the R134a refrigeration system using a two-phase ejector as an expander," *Int. J. Refrig.*, vol. 43, pp. 97–110, Jul. 2014.

[3] H. Wang, R. Peterson, and T. Herron, "Design study of configurations on system COP for a combined ORC (organic Rankine cycle) and VCC (vapor compression cycle)," *Energy*, vol. 36, no. 8, pp. 4809–4820, Aug. 2011.

[4] F. Molés, J. Navarro-Esbrí, B. Peris, A. Mota-Babiloni, and Á. Barragán-Cervera, "Theoretical energy performance evaluation of different single stage vapour compression refrigeration configurations using R1234yf and R1234ze(E)

as working fluids," *Int. J. Refrig.*, vol. 44, pp. 141–150, Aug. 2014.

[5] J. Sarkar, "Ejector enhanced vapor compression refrigeration and heat pump systems—A review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 9, pp. 6647–6659, Dec. 2012.

[6] J. M. Gonçalves, C. Melo, and C. J. L. Hermes, "A semi-empirical model for steady-state simulation of household refrigerators," *Appl. Therm. Eng.*, vol. 29, no. 8–9, pp. 1622–1630, Jun. 2009.

[7] P. a. Domanski, J. Steven Brown, J. Heo, J. Wojtusiak, and M. O. McLinden, "A thermodynamic analysis of refrigerants: Performance limits of the vapor compression cycle," *Int. J. Refrig.*, vol. 38, pp. 71–79, Feb. 2014.

[8] P. Wainaina, M. Njue, and W. Ogola, "Numerical model to optimize the refrigerant charge for maximum refrigeration capacity," *Therm. Sci.*, vol. 17, no. 4, pp. 989–995, 2013.

[9] L. Zhao, W. Cai, X. Ding, and W. Chang, "Model-based optimization for vapor compression refrigeration cycle," *Energy*, vol. 55, pp. 392–402, Jun. 2013.

[10] M. Wallace, B. Das, P. Mhaskar, J. House, and T. Salsbury, "Offset-free model predictive control of a vapor compression cycle," *J. Process Control*, vol. 22, no. 7, pp. 1374–1386, Aug. 2012.

[11] V. Jain, S. S. Kachhwaha, and G. Sachdeva, "Thermodynamic performance analysis of a vapor compression–absorption cascaded refrigeration system," *Energy Convers. Manag.*, vol. 75, pp. 685–700, Nov. 2013.

[12] H. M. Getu and P. K. Bansal, "Modeling and performance analyses of evaporators in frozen-food supermarket display cabinets at low temperatures," *Int. J. Refrig.*, vol. 30, no. 7, pp. 1227–1243, Nov. 2007.

[13] B. Li and A. G. Alleyne, "A dynamic model of a vapor compression cycle with shut-down and start-up operations," *Int. J. Refrig.*, vol. 33, no. 3, pp. 538–552, May 2010.

[14] J. Navarro-Esbrí, V. Berbegall, G. Verdu, R. Cabello, and R. Llopis, "A low data requirement model of a variable-speed vapour compression refrigeration system based on neural networks," *Int. J. Refrig.*, vol. 30, no. 8, pp. 1452–1459, Dec. 2007.

[15] P. J. Waltrich, J. R. Barbosa, and C. J. L. Hermes, "COP-based optimization of accelerated flow evaporators for household refrigeration applications," *Appl. Therm. Eng.*, vol. 31, no. 1, pp. 129–135, Jan. 2011.

[16] T. M. Yusof and A. Azizuddin, "Performance Analysis Of A Domestic Refrigerator," vol. 9501, no. May, pp. 582–591, 2010.

[17] D. Zhang, Q. B. Wu, J. P. Li, and X. Q. Kong, "Effects of refrigerant charge and structural parameters on the performance of a direct-expansion solar-assisted heat pump system," *Appl. Therm. Eng.*, vol. 73, no. 1, pp. 520–526, Dec. 2014.

[18] W. Kim and J. E. Braun, "Evaluation of the impacts of refrigerant charge on air conditioner and heat pump performance," *Int. J. Refrig.*, vol. 35, no. 7, pp. 1805–1814, Nov. 2012.

[19] J.-H. Chae and J. M. Choi, "Evaluation of the impacts of high stage refrigerant charge on cascade heat pump performance," *Renew. Energy*, pp. 1–6, Aug. 2014.

[20] J. Boeng and C. Melo, "Mapping the energy consumption of household refrigerators by varying the refrigerant charge and the expansion restriction," *Int. J. Refrig.*, vol. 41, pp. 37–44, May 2014.

[21] A. a. a. a. Al-Rashed, "Effect of evaporator temperature on vapor compression refrigeration system," *Alexandria Eng. J.*, vol. 50, no. 4, pp. 283–290, Dec. 2011.

[22] P.A. Hilton Ltd. (1998), *Schematic Diagram of R713 Refrigeration Laboratory Unit*. Experimental Operating and Maintenance Manual, Stockbridge, Hampshire. 1.

[23] B. A. Qureshi and S. M. Zubair, "Performance degradation of a vapor compression refrigeration system under fouled conditions," *Int. J. Refrig.*, vol. 34, no. 4, pp. 1016–1027, Jun. 2011.

[24] IBM Corp., "IBM SPSS Statistics for Windows, Version 20.0." IBM Corp, Armonk, NY, 2011.