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Experimental Investigation of the Performance and Energy Consumption of an Automated Ice-cube Making Machine

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors designed the study. Author RAS carried out the experimentation, did the analyses and wrote the first draft of the manuscript. Author IFT supervised the experimentation, managed the analyses of the study and review the manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: This study investigates the performance of a developed automated ice-cube making machine under controlled ambient conditions, in which its energy usage, rate of ice cube production and refrigeration system performance was analysed.
Study Design: Average ambient temperatures of 24°C and 32°C were considered for investigation in order to determine their influence on ice production capacity, rate of ice-cube making and energy consumption. The choice of the ambient temperature is based on the extreme ambient conditions under which the machine is designed to operate in a wide range of geographical regions. The refrigeration system performance was carried out under normal room temperature (average of 23°C).
Place and Duration of Study: Department of Mechanical Engineering, Federal University of Technology Akure, Ondo State Central Workshop, Between December 2017 and January 2018.
Methodology: The machine was set into operation for 5 consecutive ice production cycle during which the ice making time, harvest time, quantity of ice produced and energy consumption were recorded.

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Results: The ice production capacity, harvesting time and energy consumption show various dissimilarities at both temperatures. 0.618 kg of ice cubes were produced within an ice making cycle of 34.9 minutes, harvesting time of 1.28 minutes and total energy consumption of 0.14053 kWh at 24°C while at 32°C, the machine produced an average of 0.612 kg ice cubes within an ice making cycle of 38.5 minutes harvesting time 1.21 minutes and energy consumption of 0.15947 kWh respectively. Consequently, 13.5% more energy is consumed, with about 1% less quantity of ice produced at 32°C than at 24°C per ice production cycle.

Conclusion: Therefore, the ice making capacity of the developed machine suggests that the temperature of the environment has a strong influence on the energy consumption, but little effect on the quantity of ice produced per cycle. The refrigeration system cycle performance analysis results showed a considerably high cooling capacity of 0.379 kW during the ice-making cycle with a corresponding coefficient of performance (COP) of 2.23, and a heating capacity of 2.24 kW during the harvest cycle with a corresponding COP of 8.21. The results obtained showed that the machine is reliable in operation with minimal energy consumption.

Keywords: Performance-evaluation; ice-cube; refrigeration; automation; microcontroller; hot-gas defrosting; ice making; energy consumption.

1. INTRODUCTION

Ice making machines are used for producing refrigeration effect to freeze potable water usually in moulds into ice of various sizes and shapes- ice-cube, nugget and flake-type ice [1]. Automatic ice manufacturing machines generally include a refrigeration system having a compressor, a condenser and an evaporator; a series of individual ice forming locations; and a water supply system. The machines are designed to automatically control water feed to the evaporator, freeze the water in an ice cube mould and harvest the ice into a storage bin. The automation is achieved using auxiliary components such as floats, solenoids, switches and sensors all integrated into an electrical control system. Ice machines come in different sizes ranging from small unit producing 22.7 kg of ice per day to a commercial unit producing 1088.6 kg of ice per day [2].

Among the many methods of harvesting (usually partially defrosting) the formed ice, the hot refrigerant gas defrost method is often used due to its effectiveness and energy efficiency. However, in some cases, electrical heaters are added to increase the speed with which the ice is thawed from the mould which comes with additional energy cost [3]. The basic principle of the hot gas defrost method is stopping the cool refrigerant supply to the evaporator followed by the supply of high-pressure, high-temperature refrigerant from the compressor discharge to the evaporator. The hot gas increases the temperature of the evaporator and melts the formed ice partially so that it can freely drop into the storage bin [4].

Over the years in the field of refrigeration, the emphasis is being laid on saving energy, protecting the environment and improving refrigeration system performance. Consequently, ice machines are expected to be energy saving with better system performance while still being able to produce ice in a short period of time to meet demands. Energy consumption can be reduced greatly by optimising refrigeration equipment system performance. Efforts are being made in this regard as researchers have investigated the impact of many variables on refrigeration equipment system performance, and energy consumption.

Limited research exists in the literature on refrigeration system performance, energy consumption and efficiency of the automated ice maker. Comparison of the performance of a domestic refrigerator-freezer in terms of energy consumption when operating with and without the automatic ice maker under two temperature settings was made [5]. It was observed that there was a substantial difference in ice production rates under different thermostat settings. In another research, the energy consumption of automatic ice makers installed in domestic refrigerators was investigated [6]. The study examined each of four automatic ice maker of different configuration and their components and discussed how the operation of each component contributed to the overall energy consumption. Results showed that the ice making energy consumption is influenced by the operating temperatures inside the cabinets. It was also revealed that approximately one quarter of the energy used by a refrigerator to operate an automatic ice maker is actually used to freeze water into ice; the remaining three quarters is a result of using heaters to free the ice from the ice maker. In a study, a model was developed to simulate the operation of an automatic commercial ice machine [7]. the model is used to calculate time-varying changes in the system properties and aggregates performance results as a function of machine capacity and environmental conditions. Simulation results from the model were compared with the experimental data of a fully instrumented, standard 500 Ib capacity ice machine, operating under various ambient and water inlet temperatures. Key aggregate measures of the ice machine's performance include the freeze and harvest cycle time, energy input per 100 Ib of ice, and energy usage in 24 hours. It was reported that the model's accuracy is within 5% for a variety of operating conditions.

In this study, the production capacity, energy consumption and the refrigeration system performance of a developed automated ice cube making machine were investigated. The daily ice production capacity of the machine under two different average ambient condition (temperature) and energy consumed was experimentally determined and analyzed; and the performance of the system during the ice-making and harvest cycles for different ice production cycles were analyzed establishing performance characteristics such as the refrigeration effect (R.E), heating effect (H.E), refrigeration capacity (RC), compressor power consumption ($\dot{W}$) and coefficient of performance (COP) during cooling and heating process.

1.1 Description and Operation of the Automated Ice-cube Making Machine

Producing 24 cubes of ice in a production cycle, measuring 22 x 22 x 22 mm from 7.667×10^{-4} m^3 of circulating water, the machine is designed to work in two distinct modes: Ice-making and Harvest mode. The Ice-making mode occurs when water is circulated over the mould or freezing surface which is in contact with the surface of the evaporator and ice is being formed. The Harvest mode occurs when the bond between the ice and freezing surface is broken and the ice is released from the surface into the bin. It consists of: a water supply system including a pump which automatically and continuously circulate water over a freezing surface (a mold) which is in thermal contact with the evaporator plate assembly; a refrigeration system having a compressor, a condenser, an expansion valve and an evaporator; and a hot gas defrost system which bypasses the high-pressure and high-temperature vaporized refrigerant compressor discharge from the condenser, which is fed to the evaporator, achieved by the opening of the hot gas valve so as to achieve ice releasing from the mold. The machine and its schematic diagram showing the various components of the refrigeration system and refrigerant flow direction is shown in Fig. 1.

2. EXPERIMENTAL DETAILS

Fig. 2 is the schematic diagram of the experimental setup showing the positions of the instruments used.

The experimental setup and procedures followed in this study are discussed is two parts as follows:

2.1 Setup and Procedures for Establishing Machine Production Capacity and Energy Consumption

The machine was set operative for 5 consecutive ice production cycles (ice-making and harvesting cycles) under 24°C and 32°C average ambient temperatures, with feed water originally at 23°C. The choice of this ambient temperature is based on the ambient conditions (extreme condition) under which the machine is designed to operate in a wide range of geographical regions, for optimal condensation performance. The ice-making cycle time, harvest cycle time, the quantity of ice produced and energy consumed were recorded for each ice production cycles. The test was done three times and the mean value for each of the data set was determined. The ambient condition was maintained by running the test in a carefully controlled indoor environment such that the ambient temperature variation is within ±2°C and the average ambient temperature reading is used. Vents were open to remove heat that is been added to the room. The experiment under 24°C was carried out at a time during the day when the ambient temperature has fallen to around 24°Cand that of 32°C was carried out when the ambient temperature has risen to about 32°C.

2.2 Setup and Procedures for the Refrigeration System Performance Analysis

The machine was set operative for 3 ice production cycles under normal room temperature measuring an average of 23°C.

Parameters measured and monitored includes the ambient temperature (T_{amb}), the mold temperature (T_{mold}), recirculation water temperature (T_{wc}), the evaporator inlet temperature (T_{ei}), the compressor inlet (T_{ci}) and outlet temperatures (T_{co}) and the condenser outlet temperature (T_{condo}); which were taken with a T-type thermocouple data logger with the thermocouples placed in the locations shown in Fig. 2. pressure gauge is mounted at the suction and discharge of the compressor, and at the exit of the hot gas solenoid valve to monitor the pressure at these locations. The electrical energy consumption was monitored using digital power meters. The readings were taken in 5 minutes interval during the ice-making cycle and 20 seconds interval during the harvest cycle due to the shortness of the cycle to allow enough readings to be taken for analysis during the cycle. The readings were taken at the stated intervals to the end of each cycle for three consecutive ice production cycles (ice-making and harvesting cycles). The data obtained were used to obtain the enthalpy values at these various points to determine the performance parameters using the following set of equations.

Refrigeration effect in kJ/kg given by

$$R.E = h_{ci} - h_{ei} \tag{1}$$

Cooling rate ($\dot{Q}_e$) or refrigeration effect in kW is obtained with

$$\dot{Q}_e = \dot{m}\,(h_{ci} - h_{ei}) \tag{2}$$

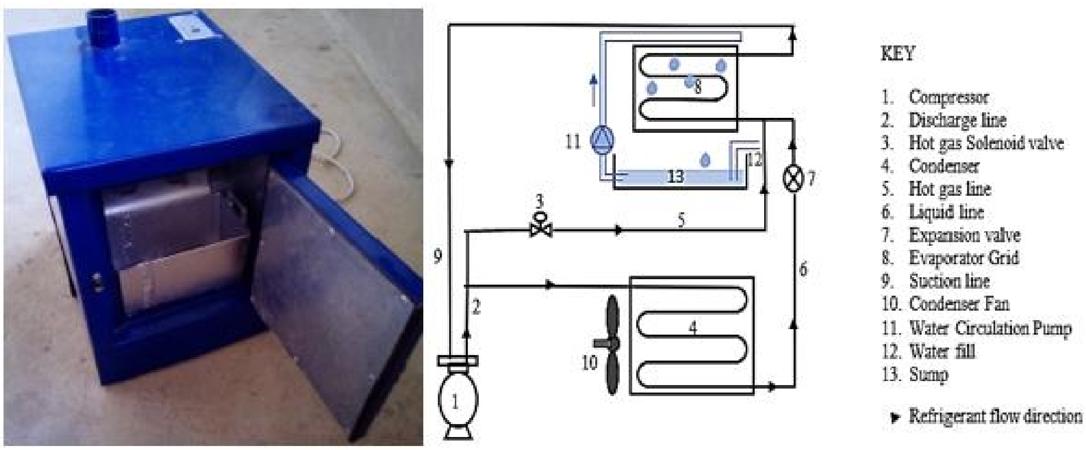

Fig. 1. Picture and schematic diagram of the automated ice-cube making machine

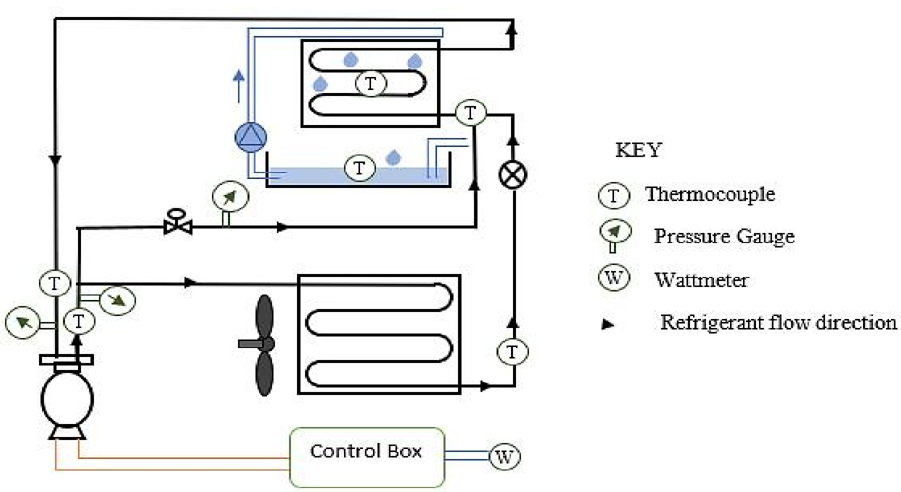

Fig. 2. Schematic diagram of the experimental setup

The heating effect in kJ/kg is obtained with

$$H.E\ (h_{ei} - h_{ci}) \tag{3}$$

Compressor work (w_{in}) in kJ/kg is obtained by

$$w_{in} = h_{co} - h_{ci} \tag{4}$$

Coefficient of performance during ice making ($COP_{cooling}$) is given by

$$COP_{cooling} = \frac{\dot{Q}_c}{\dot{W}} \tag{5}$$

Coefficient of performance during harvest ($COP_{heating}$) is given by

$$COP_{heating} = \frac{\dot{Q}_h}{\dot{W}} \tag{6}$$

Since the ice making and harvesting take place under distinct refrigeration cycles, the relevant system performance characteristics were analysed under the two cycles separately due to different cycle time and characteristics.

3. RESULTS AND DISCUSSION

3.1 Machine Production Capacity and Energy Consumption

The mean and deviation from the mean of the data obtained on testing the machine under 24°C and 32°C average ambient temperature for 5 consecutive ice production cycles is presented in Table 1 and 2 respectively.

Thus, for 24°C average ambient temperature testing condition,

Avg. quantity of ice produced per cycle= 0.618 kg

Avg. production capacity per cycle= 0.618 kg ⁄ 2174.14 secs = 0.618 kg⁄36.24 mins

Ice production capacity on 24 hours basis = 0.618 kg⁄2174.14 secs ×86400 secs
=24.6 kg

Average energy consumption per cycle = 0.14053 kWh

Approximate energy consumption per day = 0.14053 kWh⁄2174.14 secs ×86400 secs
=5.58464 kWh

For 32°C average ambient temperature testing condition,

Average quantity of ice produced per cycle= 0.6118 kg

Average production capacity per cycle= 0.6118 kg⁄2382.402 secs = 0.618 kg/ 39.7 mins

Ice production capacity on 24 hours basis = 0.6118 kg⁄2382.402 secs ×86400 secs
=22.2 kg

Average energy consumption per cycle = 0.15947 kWh

Approximate energy consumption per day = 0.15947 kWh⁄2382.402 secs ×86400 secs
=5.78333 kWh

It can be seen from Tables 1 and 2 that there is a significant reduction of about 11.9 minutes and 12.1 minutes in the ice making time after the first production cycle (FPC) when the machine was tested under 24 and 32°C average ambient temperatures respectively, while a very small reduction in the ice making time is observed in subsequent cycles under both ambient conditions. This is because the temperature of the water in circulation contained in the sump had dropped while circulating across the grid in the FPC and thus, it takes lesser time to bring the circulating water to freezing temperature in subsequent cycles. It is also observed that ice making takes longer when the machine was tested under 32°C average ambient temperature compared to the 24°C testing condition. This amount to higher ice production time with an average of 39.7 minutes compared to 36.24 minutes that was determined for 24°C ambient temperature testing condition. However, harvesting takes lesser time under 32°C ambient temperature with an average of 72.4 seconds (1.21 mins) compared to 76.7 seconds (1.28 mins) under 24°C ambient temperature. This is because the surrounding heat from the environment contributes to the defrosting of the ice. Since the higher the ambient temperature, the more the surrounding heat hasten the defrosting process, thus, the harvest time decreases with increasing ambient temperature. About 1% less quantity of ice was produced at the 32°C than at 24°C per ice production cycle. Consequently, the daily ice production capacity is thus higher under 24°C ambient condition with an average of 24.6 kg of ice cubes per day compared to 22.2 kg of the 32°C ambient condition. Therefore, the ambient condition has effect on the ice production capacity of the machine.

Table 1. Calculated mean values of the production time, quantity and energy consumption under 24°C average ambient temperature

Ice production cycle	Ice-making time (secs)	Harvest time (secs)	Ice production time (secs)	Quantity of ice produced (kg)	Energy Consumption (kWh)
1st	2732.67 ± 18.22	80.00 ± 0.667	2812.67	0.613 ± 0.0044	0.154333 ± 0.0018
2nd	2020.67 ± 10.22	77.00 ± 0.667	2097.67	0.617 ± 0.0044	0.141333 ± 0.0011
3rd	1951.67 ± 9.11	76.33 ± 0.444	2028.00	0.617 ± 0.0044	0.138333 ± 0.0016
4th	1898.00 ± 5.33	74.67 ± 0.444	1972.67	0.623 ± 0.0044	0.135667 ± 0.0016
5th	1884.00 ± 7.33	75.67 ± 0.444	1959.67	0.620 ± 0.0067	0.133000 ± 0.0007
Average	2097.402	76.734	2174.14	0.618	0.1405332

Table 2. Calculated mean values of the production time, quantity and energy consumption under 32°C average ambient temperature

Ice production cycle	Ice-making time (secs)	Harvest time (secs)	Ice production time (secs)	Quantity of ice produced (kg)	Energy Consumption (kWh)
1st	2943.33 ± 13.78	74.67 ± 0.889	3018.00	0.607 ± 0.0044	0.174333 ± 0.0024
2nd	2220.00 ± 6.00	72.67 ± 0.444	2292.67	0.613 ± 0.0044	0.162667 ± 0.0004
3rd	2158.67 ± 5.11	71.33 ± 0.444	2230.00	0.613 ± 0.0044	0.157333 ± 0.0011
4th	2122.67 ± 7.11	71.67 ± 0.444	2194.34	0.613 ± 0.0044	0.153000 ± 0.0013
5th	2105.33 ± 4.22	71.67 ± 0.444	2177.00	0.613 ± 0.0044	0.150000 ± 0.0013
Average	2310.00	72.402	2382.402	0.6118	0.159466667

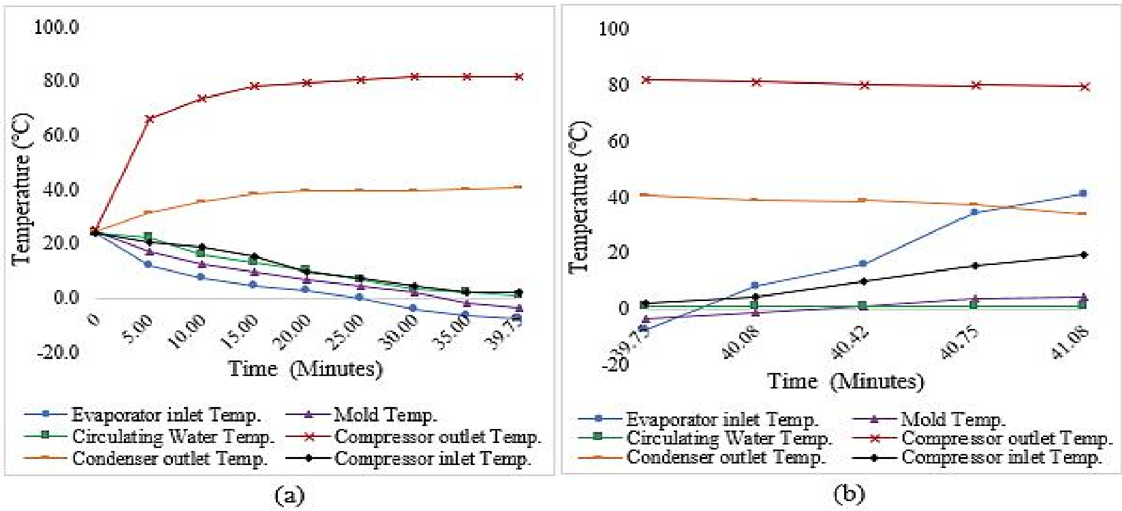

Fig. 3. Temperature variation with time at different locations on the machine during; (a) Ice-making cycle; (b) Harvest cycle of the FPC

The average energy consumption per cycle under 24°C and 32°C ambient conditions are 0.14053 kWh and 0.15947 kWh respectively as shown in Tables 1 and 2. This result was used to estimate daily energy consumption. The estimated daily energy consumption is higher under 32°C ambient temperature condition with 5.78333 kWh, while 5.58464 kWh is the estimate for the 24°C testing condition. The influence of the ambient temperature is significant on the energy consumption as about 13.5% more energy is consumed at the 32°C condition than at 24°C per ice production cycle. It should be noted that the energy consumption is however on the lower side compared to commercial ice makers which consume about 14 to 20 kWh a day [8].

3.2 Refrigeration System Performance Analysis

The performance of the refrigeration system during the first production cycle (FPC), second production cycle (SPC) and the third production cycle (TPC), under normal room temperature are discussed as follows:

3.2.1 Temperature variation with time

Figs 3-5 gives a plot of the temperature variation with time at different locations on the machine for three consecutive ice production cycles. The trend of temperature changes from one cycle to the other can be observed and comparison can be made.

The plot shows that in the first 5 minutes into operation there was a significant and drastic drop in the evaporator inlet temperature which account for 38.4% of the total temperature drop that occurred over a time of 39.75 minutes during the ice-making cycle of the FPC as shown in Fig. 3(a). This is due to the vast temperature difference that exists between the refrigerant and the surroundings which causes a sudden cooling effect on the mold and the water in circulation. Consequently, there was a significant drop in the mold temperature during this period. As the water in circulation flows over the mold, and cooling began, a gradual temperature drop was also observed on the water in circulation which continues until it reaches 0.8°C at the end of the ice-making cycle of the FPC. The lowest temperature observed at the evaporator inlet, on the mould and the compressor inlet were -7.5, -3.6 and 2°C respectively, at the end of the first ice-making cycle. It is observed that when the compressor was energized the compressor outlet temperature rises significantly from the initial value of 25 to 66.3°C in the first 5 minutes of operation and then continue to rise gradually towards the end of the cycle till it became stabilized at 81.8°C. The same pattern was also observed for the condenser outlet temperature during this cycle.

During the harvest cycle of the FPC depicted in Fig. 3 (b), a significant temperature rise was observed at the evaporator inlet in the beginning of the cycle from -7.5°C and increases continuously to 40.9°C at the end of the 60 secs cycle. This was caused by the high-temperature superheated refrigerant channelled to the evaporator during the cycle. Consequently, the mould and compressor inlet temperature also increase gradually with a total of 7.8°C and 17.4°C temperature rise respectively, at the end of the cycle. The circulating water temperature in the sump remained constant throughout the harvest cycle at 0.8°C, the value it was at the end of the ice-making cycle. This is because water circulation was stopped at the end of the ice-making cycle and there was no heat transfer between the water and the refrigerant.

It can be observed that the temperature-time plot of the subsequent ice production cycles follows an identical trend as shown in Fig. 4 and 5 owing to the steady operating condition of the machine. From the Figs 4 (a) and 5 (a) depicting the ice making cycles, it is observed that 5 minutes into the cycles, the evaporator inlet temperature falls drastically by 47.1 and 48.5°C respectively to -6.2 and -7.4°C respectively. This is because of the termination of the hot refrigerant gas supplied to the evaporator and the supply of subcooled refrigerant. During the harvest cycles

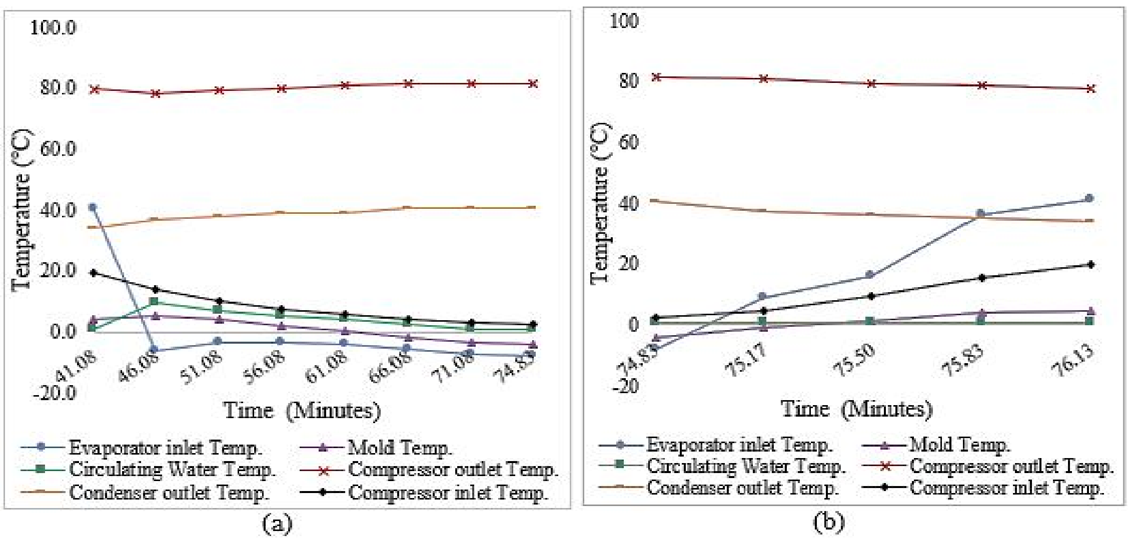

Fig. 4. Temperature variation with time at different locations on the machine during; (a) Ice-making cycle; (b) Harvest cycle of the SPC

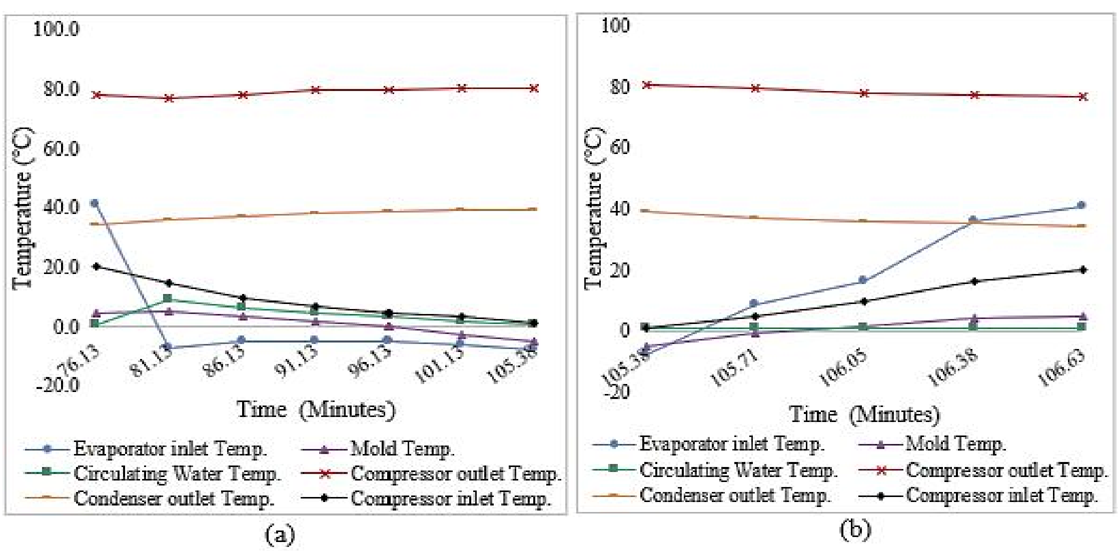

Fig. 5. Temperature variation with time at different locations on the machine during; (a) Ice-making cycle; (b) Harvest cycle of the TPC

[Figs 4 (b) and 5 (c)], the sudden temperature rise in the evaporator inlet temperature is due to the superheated refrigerant supplied to the evaporator which continues till the end of the cycle. The temperature rise for both the SPC and TPC at the end of the cycle is 48.9°C at the evaporator inlet. For the same reason discussed earlier, the circulating water temperature remains constant throughout the cycle at 0.7°C for both the SPC and TPC as shown in Figs 4 (b) and 5 (c). Meanwhile, the compressor and condenser outlets experience temperature drop throughout the cycle.

3.2.2 Refrigeration effect and cooling rate

Fig. 6 provides a comparison of the time variation of the refrigeration effect of the ice-making cycle for three consecutive ice production cycles and the cooling rate. What is desirable for an efficient system is high refrigeration effect/cooling rate with considerable small energy consumption. The general trend of the plot showed that, as time passes the refrigeration effect reduces till the end of the cycle and invariably the cooling rate too as shown in Fig. 6 (a) and (b) respectively. This general behaviour is due to the initial high temperature at the beginning of the cycles resulting in a large amount of heat needed to be removed, which reduces as the temperature falls while cooling takes place.

It is also observed that the cooling rate decreases greatly within 20 minutes into the cycles, after which the decrement was slight and then after, the cooling rate became relatively stable towards the end of the cycles. Higher refrigeration effect/cooling rate was observed in the first ice-making cycle owing to a high initial temperature of the circulating water to be iced. It should be noted that the cooling rate is generally high and this results in quick ice production by the machine compared to other refrigerators.

3.2.3 Heating rate during harvest cycles and discharge temperature

Fig. 7 provides a comparison of the time variation of the heating rate during the harvest cycles and their relationship with the compressor discharge temperature.

A high heating rate is desirable to allow quick thawing and release of the ice with less energy consumption to better the overall system energy performance. It is observed from the plot that the heating rate for each of the cycles increases throughout the cycle. This is due to the large difference in temperature of the hot refrigerant vapour and the ice. The minimum and maximum heating rate observed are 1.24 kW and 2.24 kW respectively. These heating rate values are high enough to allow quick partial thawing and release of the ice for this system. It is however observed that the compressor discharge temperature continues to decrease gradually and insignificantly throughout the cycles. The highest decrement is about 3.9°C during the TPC. This will lead to less compression work and thus, an improved system performance.

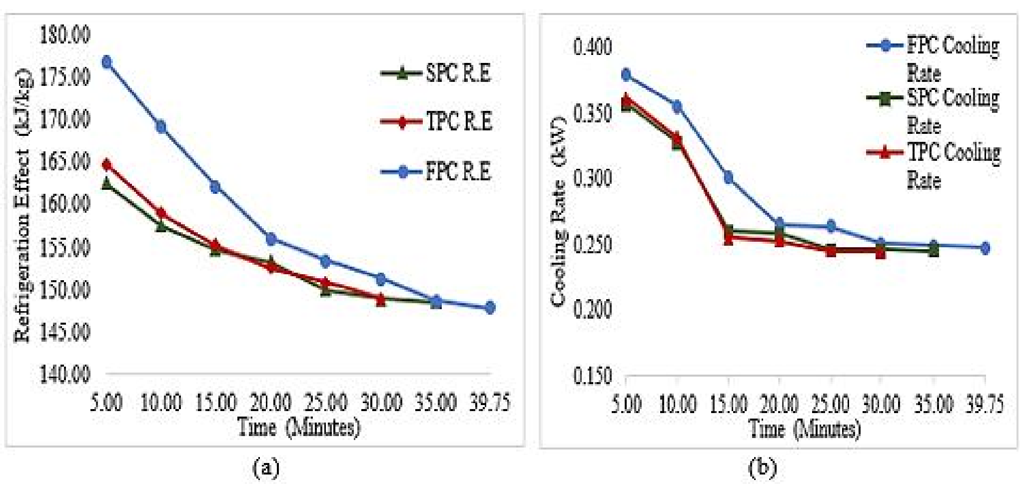

Fig. 6. Comparison of time variation of (a) refrigeration effect; (b) cooling rates of the FPC, SPC, TPC

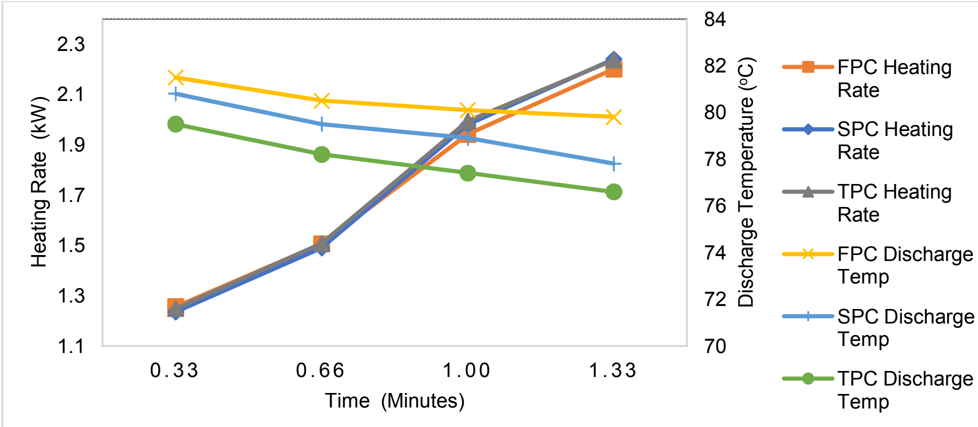

Fig. 7. Heating rate of the evaporator during harvest cycles and discharge temperature

3.2.4 Compressor work and power consumption

The variation of compressor work and the machine power consumption during the ice-making and harvest cycle for three consecutive ice productions is presented in Fig. 8 and 9 respectively. During the ice-making cycles it is observed that the compressor work increases with time throughout the cycle as shown in Fig. 8. This is because of the increasing compressor discharge temperature, resulting in more work being done by the compressor piston on the refrigerant vapour to increase its temperature and enthalpy throughout the cycle. Increasing compression work will invariably lead to increased energy demand. This explains the increasing electrical power consumption as observed from Fig. 8. The power consumption fluctuates throughout the cycle, but the fluctuations tend towards an increase. From the trends, it can be observed that the compression work is lowest during the FPC followed by the SPC and highest during the TPC owing to the increasing temperature difference between the compressor discharge and the suction from the FPC to the TPC.

On the contrary, during the harvest cycles, the work of compression decreases gradually till the end of the cycle as shown in Fig. 9. This is attributed to the decreasing compressor discharge temperature, resulting in lesser work being done by the piston on the refrigerant vapour. The reduction in work of compression explains the decrement in power consumption after an initial rise in the first few seconds into the cycle. It can be observed that the power consumption during the harvest cycles is higher than the ice making cycles due to the additional energy used for energising the hot gas solenoid valve throughout the cycle. It is worthy to be noted that the energy consumption of the machine is lesser compared to those machines using the electrical defrost method or a combination of both electrical and hot gas defrost method. this is because hot gas defrosting offers an inexpensive source of heat as compared to methods using other heat sources.

3.2.5 Coefficient of performance (COP) during ice-making and harvesting

The COP of the machine is an expression of the machine's efficiency, which value includes energy consumption of all power consuming auxiliaries. Fig. 10 (a) and (b) provides a comparison of the variation of COP during the cooling and heating cycles for three consecutive ice productions respectively. During ice-making cycle the general trend is the $COP_{cooling}$ falls over time as cooling is achieved throughout the ice-making cycles as seen from Fig. 10 (a). This trend is attributed to the decreasing cooling rate over time due to the decreasing recirculating water temperature. Also, the increasing power consumption due to increasing compression work is also a factor. During cooling, the highest $COP_{cooling}$ observed was 2.23 within the first 5 minutes into the cycle during the FPC. Followed by 2.13 and 2.03 during SPC and TPC respectively. Then for the next 15 minutes, the $COP_{cooling}$ falls drastically to 1.52, 1.37 and 1.29 during the FPC, SPC and TPC respectively.

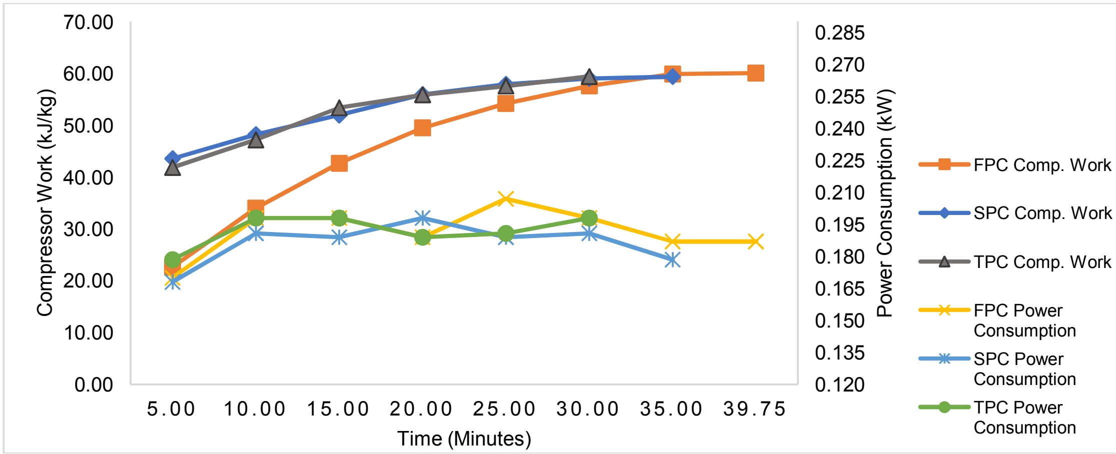

Fig. 8. Variation of compressor cork and power consumption over time during ice-making cycles

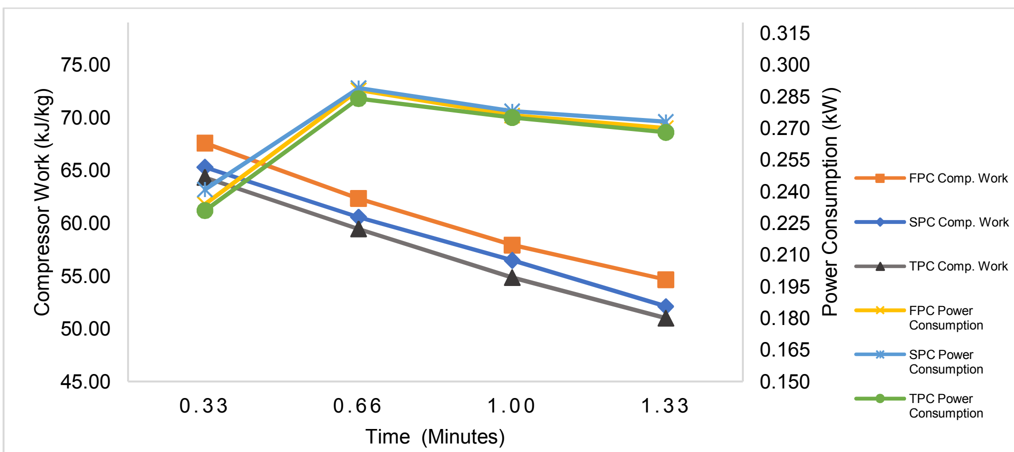

Fig. 9. Variation of compressor work and power consumption over time during harvest cycles

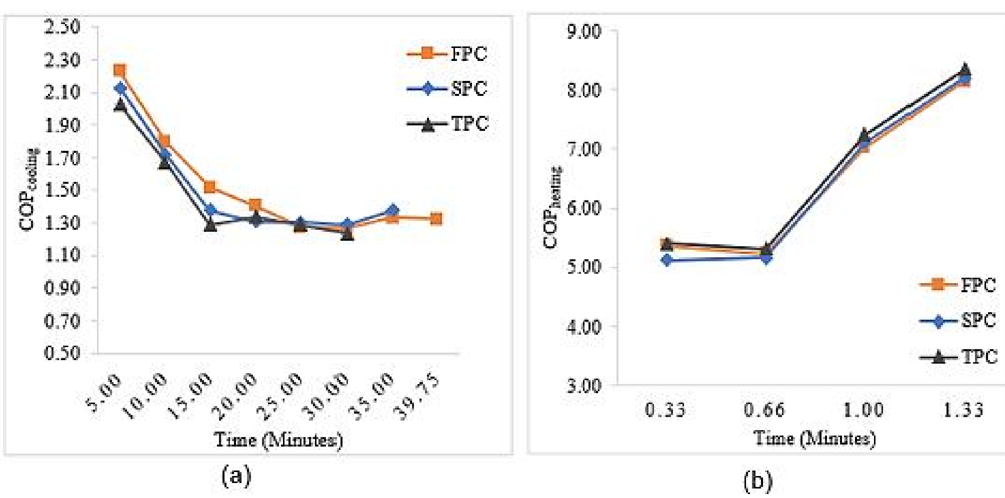

Fig. 10. (a) COP (cooling) during ice-making cycles; (b) COP (Heating) during harvest cycles

During the harvest cycle, the general trend is the $COP_{heating}$ increases with time throughout the cycles as observed from Fig. 10 (b). The increasing COP is due to the increasing heating rate coupled with reducing power consumption during the harvest cycle. The highest $COP_{heating}$ observed is 8.35 during the TPC followed by 8.21 and 8.15 during the SPC and FPC respectively. There was a very small drop in COP in the first few seconds into the cycle due to increasing power demands and then afterwards the COP rises significantly owing to a significant reduction in power demands.

4. CONCLUSION

This study investigates the performance of an automated ice cube making machine under a controlled ambient condition (24°C and 32°C) and energy usage. Key performance measure includes the ice production capacity, freeze and harvest cycle time, energy consumption and refrigeration system performance. It was found that at 24°C, an average of 0.681 kg of ice was produced per cycle of 36.24 mins (24.6 kg/day) with minimal energy consumption of 0.14053 kWh; while at 32°C the quantity of ice cube production decreased to 0.6118 kg per cycle of 39.7 mins (22.2 kg/day) with increased energy consumption of 0.15947 kWh. As a result, 13.5% more energy is consumed, with about 1% less quantity of ice produced at 32°C than at 24°C per ice production cycle. Hence, the ambient temperature has a strong influence on the energy consumption of the machine but however has an insignificant effect on the quantity of ice produced per cycle. The cooling capacity of 0.379 kW was obtained for the machine with a corresponding COP of 2.23, while the heating capacity of 2.24 kW was determined for the evaporator during the harvest with a corresponding COP of 8.21. The results have shown that the machine has a very good ice making capability, stable and reliable operation with minimal energy consumption.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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