EXPERIMENTAL INVESTIGATION OF A STIRLING CYCLE COOLED DOMESTIC REFRIGERATOR

Emre Oguz*, R&TD Engineer, Research & Technology Development Center
Arcelik A.S. 81719, Tuzla Istanbul, TURKEY; Tel.: +90 216 585 8446;
Fax : +90 216 423 3045 E-mail: emre.oguz@arcelik.com *Author for Correspondence

Fatih Ozkadi, R&TD Specialist, Research & Technology Development Center
Arcelik A.S. 81719, Tuzla Istanbul, TURKEY; Tel.: +90 216 585 8448;
Fax : +90 216 423 3045 E-mail: fatih.ozkadi@arcelik.com

ABSTRACT

A free piston Stirling cooler which is a recent prototype of a private company was integrated into a domestic refrigerator cabinet. A closed loop thermosyphon system was constructed by connecting a heat exchanger which was placed on the cold head of the Stirling cooler directly to another heat exchanger placed in the cabinet as evaporator. On the other hand, since effective heat transfer is needed on the warm head to obtain efficient operating conditions, an extended surface aluminium heat exchanger was placed on the warm head of the cooler and a fan was used to obtain forced convection heat transfer. The prototype refrigerating unit was tested for different charge quantities of the refrigerant filled in the thermosyphon loop as well as for different input voltages of the cooler. The temperatures of the key points on the cold side thermosyphon, the temperatures of the shelves of the cabinet and the input power of the Stirling cooler were recorded.

INTRODUCTION

During the 1990s ozone depletion and other environmental issues related to CFC and HFC refrigerants used in mechanical vapor compression systems in domestic refrigerators have led to considerable amount of research and development activities in the field of refrigeration. The recent proposals and discussions on energy efficiency index regulations on the other hand, have imposed more strict targets for domestic refrigerator manufacturers. While the commercialised variable capacity compressor technology or the linear compressor technology which currently seems to be at the development stage can be possible successors of the conventional vapor compressors in the future; research on alternative refrigeration methods such as Stirling cycle, magnetic cooling and thermoacoustics have reached to a certain level and these technologies can also be considered as challenging alternatives to conventional compressors.

A free piston Stirling cooler is basically a pressure vessel which operates by shuttling a certain amount of Helium gas back and forth by the combined movement of the piston and the displacer and can be determined by a cold head where thermal energy is extracted from the surroundings and a warm head where heat is rejected to the environment. Past and recent calorimetric studies on free piston Stirling coolers showed that a COP value higher than 2.5 could be reached at certain operating conditions depending on these cold and warm head temperatures [1, 2]. Another advantage of the free piston Stirling coolers is declared to be the high COP levels at low heat loads – even lower than 30 W – which can be maintained by modulating the input voltage and hence the refrigeration capacity of the Stirling cooler.

Although there are several heat transfer mechanisms – such as forced fluid convection, forced air convection or thermosyphon method – that can be applied while integrating the Stirling cooler to a domestic refrigerator cabinet, recent studies has focused on the thermosyphon system since no additional power is needed to circulate the heat transfer media. In a recent study by Berchowitz et al., the test results of a Stirling cycle cooled portable cool box are given in detail [3]. A 40 W free piston Stirling cooler had been integrated to a 40 liter portable cool box where the thermosyphon system had been manufactured from 3 mm inner diameter copper tubing. In the thermosyphon system which had consisted of a condenser placed on the cold head of the cooler and an evaporator, carbondioxide had been used as the heat transfer fluid [3]. Presented experimental results are stated to be much better than Peltier or small vapor compression systems.

An interesting study on the application of two thermosyphon systems to a domestic freezer is presented by Larsson et al. [4]. Two thermosyphon systems had been designed; one for cooling the warm side of the compact cooler and the other for heat extraction from the cabinet. While propane had been chosen as the refrigerant for the warm side thermosyphon system; carbondioxide is stated to be used as refrigerant in the cold side thermosyphon [4]. According to the test results the lowest cabinet temperature achieved is declared to be –11°C while the saturation temperature of carbondioxide and the cold head temperature of the cooler were –18°C and –37°C, respectively.

EXPERIMENTAL SETUP AND PROCEDURE

Description of the Prototype Refrigerator

A commercially available larder refrigerator model which is described in detail in the following sections was selected as the first prototype to integrate the Stirling cooler. After removing the original components such as compressor, condenser and capillary tube the cabinet was finally turned upside down to enable the application of the thermosyphon system. The free piston Stirling cooler, the thermosyphon system for the cold side, the cabinet and the heat exchanger for cooling the warm side of the Stirling cooler are described in the following sections.

Free Piston Stirling Cooler

The free piston Stirling cooler used in this study is a first model prototype of a private company. The cooler can be defined as a hermetic unit where Helium gas is shuttled back and forth by the combined movements of the piston and the displacer. While the gas is compressed by the piston thermal energy is rejected to the environment whereas heat is extracted from the surroundings during the expansion phase of the gas; where both processes occur theoretically at constant temperature.

The spesific cooler integrated to the larder refrigerator in this study is a 220 V – 50 Hz AC unit and has three parameters that effect its refrigeration capacity and thermal performance when considered as a black box; namely the cold head temperature, the warm head temperature and the input voltage. Though there are certain differences, the cold and warm head temperatures are similar concepts to the evaporation and condensation temperatures in conventional vapor compression systems and the refrigeration capacity and COP of the cooler increase as the cold head temperature increases at constant warm head and drive voltage conditions. The input voltage on the other hand has also a positive linear effect on the refrigeration capacity but almost no effect on the COP level of the cooler [2].

Thermosyphon System

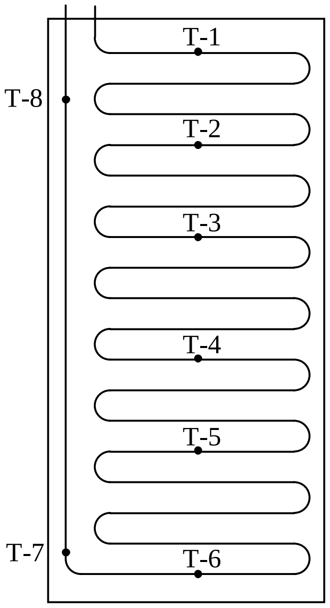
The thermosyphon system constructed in this study is basically a closed loop which is consisted of two heat exchangers; namely, the evaporator and the condenser. The evaporator is directly connected to the annular heat exchanger which is placed on the cold head of the Stirling cooler. The annular heat exchanger is used as a condenser and since the two-phase refrigerant flow is driven by the liquid column that is formed at the exit of the condenser, no other components such as a liquid refrigerant pump is needed between the two heat exchangers.

The evaporator which is manufactured from an aluminium sheet and oval aluminium piping is schematically given in Figure 1.a; where the temperature measurement points are also shown as T-1 to T-8. The side view of the upside-down cabinet and the location of the evaporator together with the condenser which is placed on the cold head of the Stirling cooler are given in Figure 1.b. This figure also includes the placement of the shelves in the cabinet with the respective 3” temperature measurement sensors shown as C-1 to C-6.

The rear view of the top portion of the cabinet – formerly the compressor compartment – where in this study the Stirling cooler and the condenser are placed is given schematically in Figure 2.a. After connecting the condenser to the evaporator, the thermosyphon system is filled with a certain amount of a refrigerant such as R134a or isobutane. When the cooler is turned on, the temperature of the cold head starts to decrease extracting heat from the refrigerant and the refrigerant condenses on the inner surfaces of the annular heat exchanger forming a liquid column between the condenser outlet and the evaporator inlet. When the amount of the liquid reaches a certain level, refrigerant circulation in the system begins with a sharp decrease in the temperature of the evaporator lines receiving liquid refrigerant. When the pressure drop of the two-phase flow in the system is balanced by the pressure difference created by the liquid column, the system reaches steady-state and hence a constant rate of massflow through the evaporator.

Cabinet and Warm Side Heat Exchanger

The overall outer dimensions of the cabinet given in Figure 1.b is 1420 × 540 × 540 mm and the interior volume of the cabinet is approximately 250 lt. The cabinet, prior to the integration of the Stirling cooler, is tested both for the heatgain and energy consumption with the original compressor. The appliance constant (UA) is obtained by the so-called “reverse heat leak” test where an electric heater and a fan were placed in the cabinet and +25°C was obtained inside the cabinet in an environment of +5°C. Since the compressor was not running during the test, dividing the total heat load by the temperature difference yielded an appliance constant of approximately 1.25 W/K.



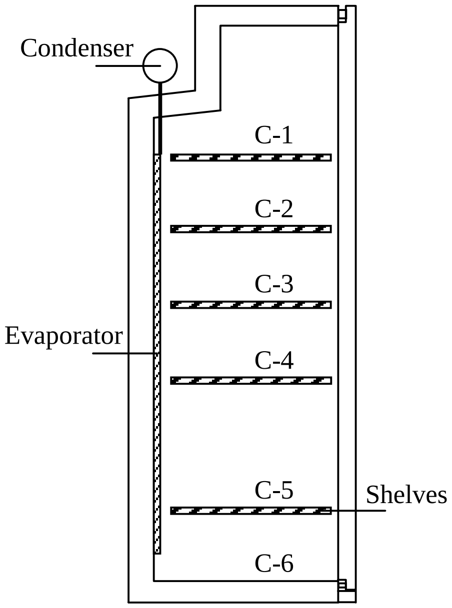
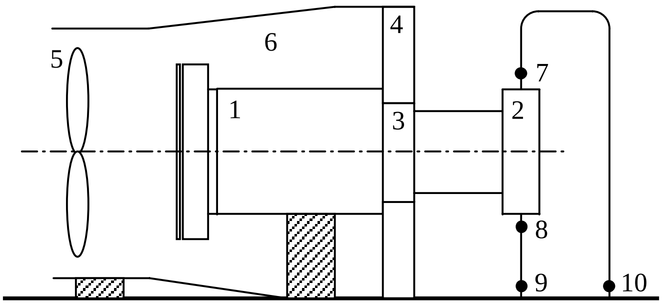


Figure 1.a : Schematic of the evaporator of the thermosyphon system.
Figure 1.b : Upside-down cabinet, location of the evaporator, condenser and the shelves.



1 : Stirling Cooler
2 : Condenser
3 : Warm Head of the Cooler
4 : Warm Side Heat Exchanger
5 : Fan
6 : Plenum
7 : Condenser Inlet
8 : Condenser Outlet
9 : Evaporator Inlet
10 : Evaporator Outlet

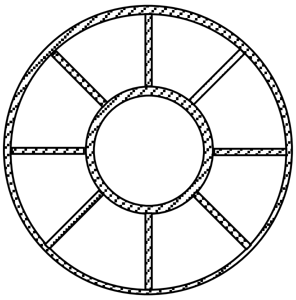


Figure 2.b

Figure 2.a : Schematic of the Stirling cooler, condenser and evaporator connections.
Figure 2.b : Conceptual design of the warm side heat exchanger.

During the operation of the Stirling cooler, thermal energy is rejected at the warm head and therefore a heat transfer mechanism should be applied to enhance the heat transfer and to keep the warm head temperature as low as possible. In this study an extended surface aluminium heat exchanger is designed and manufactured for this purpose which is schematically given in Figure 2.b. While the inner dimension of the heat exchanger is determined by the outer diameter of the warm head of the cooler, the number of the fins and the outer diameter of the heat exchanger apparently depends on the spesific application. A fan is also used to increase the convective heat transfer coefficient.

Instrumentation and Experimental Procedure

The prototype refrigerator is tested in a conditioned chamber where the temperature and the humidity of the ambient air are automatically controlled. The chamber has its own stationary measurement equipment and the temperature, voltage, current and power measurements are ensured to be within ±0.3°C, ±0.5 V, ±0.01 A ±0.5 W respectively. In addition to the 8 points on the evaporator of the thermosyphon system and the 6 points in the cabinet; evaporator outlet, condenser inlet and outlet and Stirling cooler warm and cold head temperatures are measured. The temperature of the ambient air is recorded at two locations where the sensors were placed at both sides of the cabinet. The input voltage to the cooler was measured as well as the current and power consumption of the cooler. The sampling frequency for all of the tests is 1 Hz.

At the beginning of each test the input voltage of the cooler is adjusted to a certain value and steady-state operation is observed after a certain time interval which is typically 24 hours. After the steady-state period is determined, which ranges from 240 minutes to 1440 minutes, the average values of the parameters are calculated for that spesific test and accepted as the test result.

The ambient temperature is 25 ± 0.5°C for all of the tests and during the specified steady-state intervals the temperatures inside the cabinet are well within ± 0.3°C for 240 minute tests and ± 0.7°C for the tests that last longer than 1000 minutes.

TEST RESULTS

In order to determine the effect of the charge quantity and input voltage, 11 tests are conducted with R134a as the refrigerant of the thermosyphon system. The cold head temperature, power consumption of the Stirling cooler, evaporation temperature and the average temperature inside the cabinet are given in Figure 3 for different input voltage and refrigerant charge levels. An important point to note is the calculation method of the evaporation temperature. Since, depending on the charge quantity of the refrigerant, superheat was observed in the evaporator for some cases, the evaporation temperature is calculated as the average temperature of the evaporator lines that do not contain superheat (e.g. T-1 through T-4). This issue is addressed also in Figure 4. As expected, the cold head, evaporation and average cabinet temperatures decrease as the input voltage of the Stirling cooler is increased. However, while cold head temperature is higher when switched from 46 to 38.5 grs, it is considerably lower when switched from 38.5 to 29.2 grs. This may be due to the partial blockage of the two-phase flow because of the excess liquid refrigerant accumulation at the bottom line of the evaporator for 46 grs; and insufficient liquid and therefore driving force for 29.2 grs which in turn effects the rate of massflow and condensation characteristics in the condenser, which is placed on the cold head of the cooler. The average cabinet temperature profiles on the other hand are similar to the evaporation temperature characteristics. However, the average temperature inside the cabinet is lower for 38.5 grs for the same input voltages. This may be explained by the higher cold head temperature and accordingly higher refrigeration capacity for 38.5 grs in which case the rate of massflow should also be optimal supporting the arguments about liquid refrigerant blockage and insufficient liquid column height.

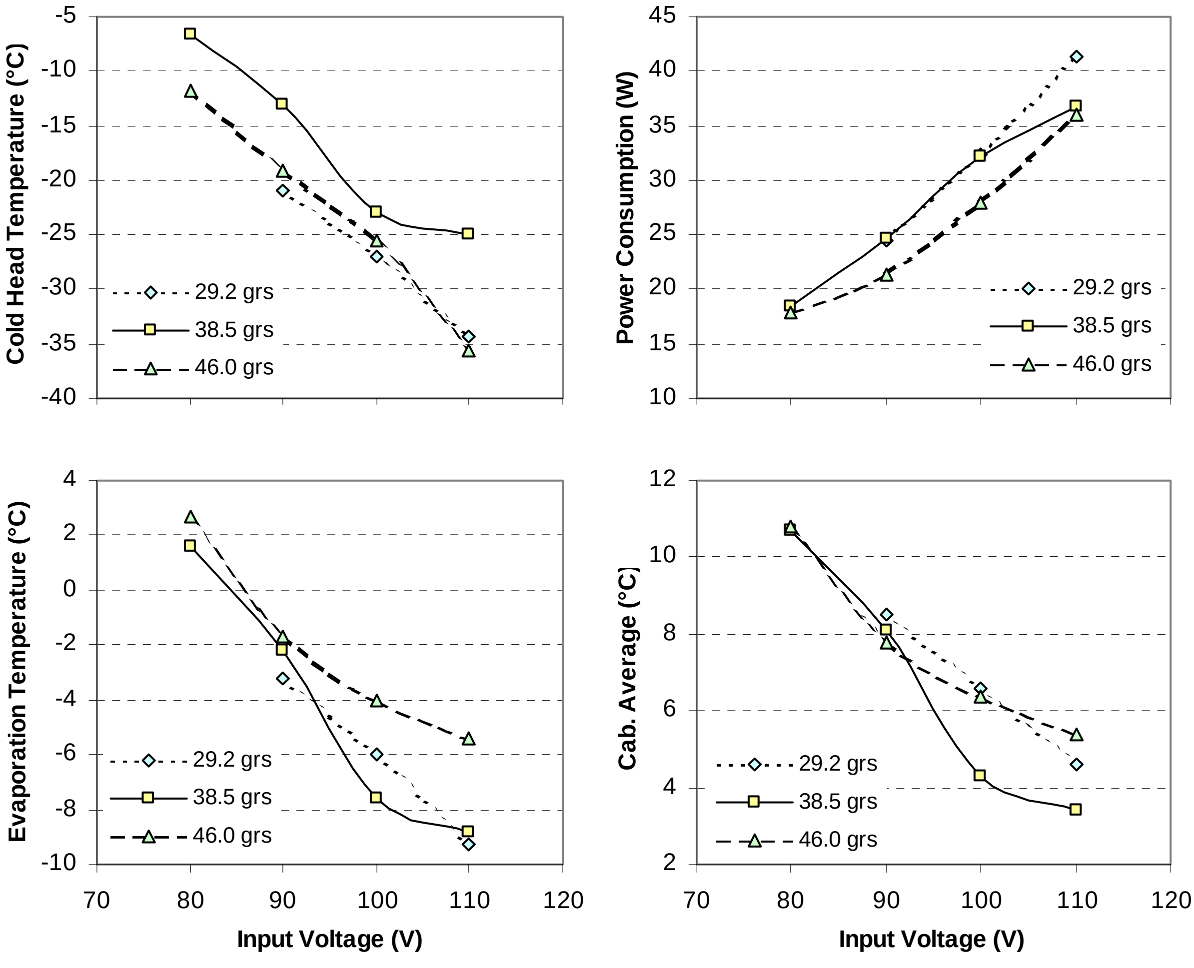


Figure 3 (a) Cold head temperature (b) Power consumption (c) Evaporation temperature and (d) Cabinet average temperature vs input voltage for different charge quantities of R134a.

In Figure 4 steady-state period of 29.2 gr R134a test at input voltage of 110 V is given. Referring back to Figure 1.a; T-2, T-3 and T-4 are not shown for clarity since they are very close to T-1 (-9.3°C). However, superheat is observed at point T-5 (-4.2°C) and onwards at T-7 (-1.7°C) and at T-9 (10.2°C) which is the evaporator outlet temperature measured outside the cabinet.

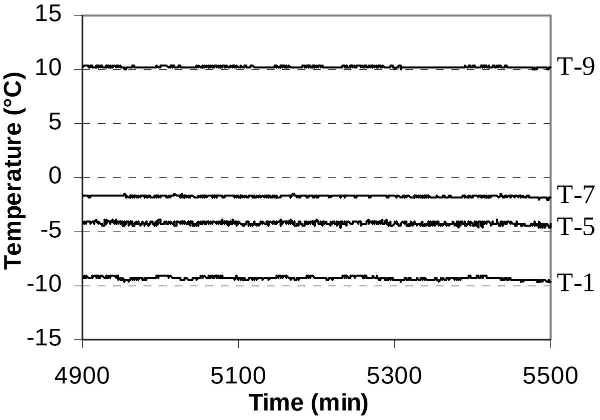


Figure 4. Steady-state period of 29.2 gr R134a test at input voltage of 110 V.

The power consumption given in Figure 3(b) does not include the fan power. Originally a no-frost appliance fan is used but since the fan motor technology has improved considerably a fan with a power consumption of 2 W can be chosen; hence it is thought to be better to focus on the power consumption of the Stirling cooler. For an average cabinet temperature of 5°C the interpolation of the data of 38.5 gr tests yields a power consumption of approximately 30.5 W which results with an energy consumption of 732 Wh/24h at 25°C ambient temperature. For the spesific refrigerator cabinet under consideration this value equals an energy efficiency index of 88 with an appliance label C.

THEORETICAL ANALYSIS

In this section, a simple theoretical analysis based on both previous experimental results and fundamental heat transfer concepts is presented. Previous studies showed that the COP of this spesific cooler can be calculated by the equation

$$\mathrm{COP} = 1.5854 \times \mathrm{Ln}\left(\mathrm{COP_C}\right) - 0.8391 \tag{1}$$

where $\mathrm{COP_C}$ is the Carnot COP based on the cold and warm head temperatures. This equation, which was derived from calorimetric data obtained for input voltages between 80 and 100 V at a constant warm head temperature of 30°C, is taken from a recent study [5] which contains similar test results to the previous calorimetric measurements [2]. Refrigeration capacity on the other hand can be represented as a linear function of cold head temperature for a certain input voltage and warm head temperature [2, 5]. Since the cold and warm head temperatures are known for the prototype refrigerator tests, COP, capacity and input power of the cooler can be calculated using the equations obtained from calorimetric data. These values are given in Table 1.

After calculating the COP by equation (1) as a function of Carnot COP, which is based on experimental values of cold and warm head temperatures, refrigeration capacity of the cooler is also calculated. Dividing these values to each other yields a calculated input power value which is shown in row 12 of Table 1. It can be seen that the calculated values are in ± 10 % agreement with the experimental results which is a little bit higher than expected. The main reason for this discrepancy is thought to be the difference in the warm head temperature. Since the appliance constant is known, the heatgain of the cabinet and the heat leak to the system can be calculated as follows

$$\mathrm{Q_{Heatgain}} = \mathrm{UA_{Cabinet}}\left(\mathrm{T_{Ambient}} - \mathrm{T_{AC}}\right),\ \mathrm{Q_{Heatleak}} = \mathrm{Q_{Capacity}} - \mathrm{Q_{Heatgain}} \tag{2}$$

where $\mathrm{T_{AC}}$ is the average cabinet temperature, $\mathrm{Q_{Heatleak}}$ is the heat transfer that occurs to the system from the ambient and $\mathrm{Q_{Capacity}}$ is the calculated capacity of the cooler. Though the condenser and the refrigerant line outside the cabinet is insulated to a certain extent, considerable amount of heat seems to be transferred to the system. Cabinet design changes should be made to eliminate this heat leak.

Table 1. Calculated and experimental parameters for prototype refrigerator tests.

	29.2 grs R134a		38.5 grs R134a		46.0 grs R134a	
	90 V	100 V	90 V	100 V	90 V	100 V
Cold head (°C)	-21.0	-27.0	-13.1	-23.0	-19.2	-25.6
Warm head (°C)	32.0	34.2	33.3	35.1	31.4	32.8
Evaporation (°C)	-3.2	-6.0	-2.2	-7.6	-1.7	-4.0
Average cabinet (°C)	8.5	6.6	8.1	4.3	7.8	6.4
Ambient (°C)	24.7	25.2	25.2	25.2	24.7	24.9
Input power (W)	24.4	32.3	24.6	32.1	21.4	28.0
Calculated capacity (W)	36.5	41.6	41.7	44.9	37.7	42.8
Carnot COP	4.76	4.02	5.60	4.31	5.02	4.24
Calculated COP	1.634	1.367	1.893	1.475	1.718	1.451
Calculated input power (W)	22.36	30.43	22.02	30.41	21.95	29.47
Input power error (%)	8.3	5.8	10.5	5.3	-2.6	-5.2
Heatgain of the cabinet (W)	20.25	23.25	21.38	26.13	21.13	23.13
Heat leak to the system (W)	16.29	18.36	20.32	18.74	16.59	19.62
Evaporator overall UA (W/K)	N/A	N/A	2.08	2.20	2.22	2.22
Condenser outlet (°C)	N/A	N/A	-1.1	-6.1	-1.0	-3.1
Condenser overall UA (W/K)	N/A	N/A	3.47	2.65	2.07	1.90

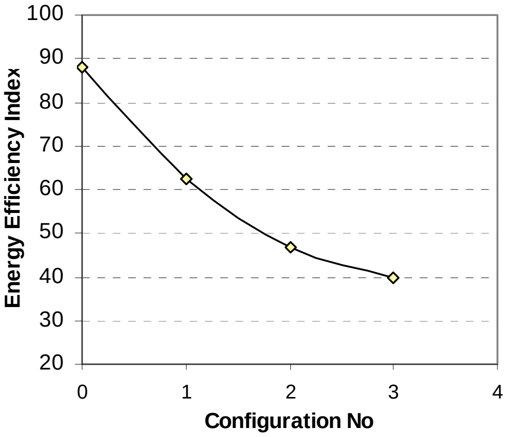
For simplicity, the heatgain of the cabinet is thought to be equal to the capacity of the evaporator and an overall heat transfer coefficient (which also includes the efficiency of the aluminium plate acting as a fin) is calculated as follows

$$UA_{Evap} = Q_{Heatgain} / \left(T_{AC} - T_{Evap}\right) \tag{3}$$

where T_{Evap} is the evaporation temperature which is an experimental value. This calculation results with an overall evaporator performance of 2.1 to 2.2 W/K for the four cases. 29.2 gr tests are not included in this calculation due to the high superheat in the evaporator lines. The condenser outlet temperatures, which are on average 1.5°C higher than the evaporation temperature, are also given in Table 1. These values are used to calculate the overall condenser performance as follows

$$UA_{Con} = Q_{Capacity} / \left(T_{CO} - T_{CH}\right) \tag{4}$$

where T_{CO}, the condenser outlet temperature, is taken to be equal to the condensation temperature and T_{CH} is the temperature of the cold head of the Stirling cooler.



Configuration	0	1	2	3
Heatgain (W)	25.0	22.5	20.0	17.5
Heat leak (W)	18.7	14.9	11.2	7.5
Evaporator UA (W/K)	2.20	2.42	2.64	2.86
Condenser UA (W/K)	2.65	2.92	3.18	3.45
Energy cons. (Wh/24h)	732	518	390	331
Energy efficiency index	88	62	47	40

Figure 5. Potential energy efficiency improvement of the current prototype Stirling cycle cooled refrigerator.

In order to have a better picture of the potential energy efficiency improvements a backward calculation procedure is applied. Cabinet heatgain and heat leak to the system is reduced, evaporator and condenser performances are increased and the evaporation temperature is calculated by equation (3). Condensation temperature is estimated to be 1.5°C higher than the evaporation temperature and then the cold head temperature is calculated by equation (4). Warm head temperature is assumed to be 35.1°C and the COP, which is independent of the input voltage, is calculated by equation (1). Hence, dividing the capacity by the COP value the input power of the cooler is obtained. The results are given in Figure 5 in terms of energy efficiency index.

CONCLUSION

A prototype Stirling cycle cooled domestic refrigerator which operates with a thermosyphon system is built and tested at different input voltages and different charge quantities of refrigerant R134a. According to the results of the current study it may be concluded that :

- The free piston Stirling technology is a challenging alternative to be used instead of conventional compressors.

- Free piston Stirling coolers can be integrated into domestic refrigerator cabinets in several ways including the thermosyphon system and the forced air convection heat transfer mechanism. Since there are no additional components consuming energy in the thermosyphon system, this method can be preferred for both cold and warm sides of the cooler. However, more theoretical and experimental research is needed on thermosyphon systems to estimate the heat transfer and pressure drop.

- Structural design changes in the cabinet are needed while integrating the Stirling cooler. The geometry of the evaporator, the location of the Stirling cooler and the insulation system should be re-designed to benefit the potential advantages of the Stirling cooler.

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