Increasing Energy Efficiency of Domestic Refrigerator Using Single Thermoelectric Module & Water Cooling of Condenser

Sagar D. Patil
Mechanical Engineering department, Indira College of Engineering and Management, Pune
Savitribai Phule Pune University, Maharashtra, India

Prof. Kiran D. Devade
Mechanical Engineering department, Indira College of Engineering and Management, Pune
Savitribai Phule Pune University, Maharashtra, India

Abstract- The study deals with hybrid refrigerator that combines thermoelectric (TER) and vapor compression refrigeration (VCR) and also entail experimental details of combined VCR & TER system. Objective is to configure hybrid refrigerator by introducing single Peltier module (TER) in domestic refrigerator and to analyze compressor cycles of conventional refrigerator with TER to increase energy efficiency of vapor compression cycle. For this comparison of standalone VCR and Hybrid VCR+TER system is carried out. A Peltier module of size 4cm×4cm×0.4cm is introduced in the refrigerator cabinet & the effect on energy efficiency in terms of trip time of compressor is recorded. The effect of Air cooled & Water cooled condenser with TER in different structures is also investigated. It is observed that by introducing thermoelectric effect, energy efficiency of VCR is increased by almost 15.72 % annually. Thus ultimately improving COP of the hybrid system with better control on temperature over the total run time.

Keywords – Energy Efficiency, thermoelectric effect, energy consumption, savings, Peltier module, Cyclic TER, Intermediate TER.

I. Introduction

Refrigerator and air conditioners are the most energy consuming home appliances. 40-70% of total energy consumption of a country is utilized for air conditioning and cooling indoor air. For this reason many researchers had performed work to enhance performance of the refrigeration systems. Most of the research work done so far deals with an objective of low energy consumption. [1]

In domestic refrigerators, the most used cooling system is vapor compression, as it has good value of Coefficient of performance (COP). However, the temperature control inside compartment is inaccurate because of compressor tripping cycles. This fact is undesirable in case of food preservation e.g. fishes, meat and fruits. Also VCR gives direct contribution to greenhouse effect resulting from gas leakage. They are noisy, bulky, costly, difficult to install and suitable only for large cooling capacity.

Whereas thermoelectric refrigeration provides good control over temperature control inside the compartment due to facility of controlling supplied voltage and thus adjust cooling power as required. Also these devices are more compact and quite due to absence of any moving part. However, TER devices has a lower value of COP and thus they consume more power. [2] Thus it is required to develop such a technology which combines the advantages of VCR and TER i.e. high COP and better temperature control. Hence this desire leads to development of hybrid refrigerator, a combination of VCR and TER technologies.

Nomenclature

COP	Coefficient of performance
CTER	Cyclic Thermoelectric Refrigeration
CWC	Cyclic Water Cooled
DC	Direct Current
I	Current [A]
ITER	Intermediate Thermoelectric Refrigeration
IWC	Intermediate Water Cooled
K	Conduction heat transfer coefficient [$Wm^{-1}K^{-1}$]
P	Input power [W]
Q	Rate of heat transfer [W]
R	Total electrical resistance [Ω]
T	Absolute temperature [^0C]
TER	Thermoelectric Refrigeration
V	Voltage [V]
VCR	Vapour Compression Refrigeration
Z	Figure of merit [1/K]

Subscripts

C	Cold junction side
H	Hot junction side

Greek Letters

α	Seebeck coefficient [VK^{-1}]

Gao Min et al. (2006) [3] investigated number of prototype thermoelectric refrigerators and their cooling performances evaluated in terms of the coefficient-of-performance, heat-pumping capacity and cooling-down rate. The coefficient-of-performance of a thermoelectric refrigerator is found to be around 0.3–0.5 for a typical operating temperature at 50^0 C with ambient at 250^0 C. The potential improvement in the cooling performance of a thermoelectric refrigerator is also investigated employing a realistic model, with experimental data obtained from this work. The results show that an increase in its COP is possible through improvements in module contact resistances, thermal interfaces and the effectiveness of heat exchangers. The energy efficiency of thermoelectric refrigerators, based on currently available materials and technology, is still lower than its compressor counterparts. However, a marketable thermoelectric refrigerator can be made with an acceptable COP. Moreover, further improvement in the COP may be possible through improving module contact-resistances, thermal interfaces and heat exchangers. With its environmental benefit, a thermoelectric refrigerator provides an alternative to consumers who are environmentally conscious and willing to spend a little bit more money to enjoy their quiet operation, and more precise and stable temperature control. [3]

Riffat et al. (2004) [4] compares the performance of three types of domestic air-conditioners, namely the vapor compression air-conditioner (VCAC), the absorption air-conditioner (AAC) and the thermoelectric air conditioner (TEAC). The basic cycles of the three types of air-conditioning systems are described and methods to calculate their coefficients of performance are presented. There are three main types of air-conditioning systems, each with their specific merits and disadvantages. Vapor compression air-conditioners have a high COP and large cooling/heating capacities but their use of ozone-depleting CFCs and noisy operation, especially in the case of window-type air-conditioner, are significant disadvantages. A split-system central air-conditioner, which has an outdoor metal cabinet containing the condenser and compressor and an indoor cabinet containing the evaporator, may mitigate system noise, and use of new refrigerants, such as R134a to replace CFCs, may reduce damage to the ozone layer, but the COP of the system is also reduced when alternative refrigerants are used. Absorption air-conditioners have intermediate values of COP and the advantage of utilizing waste heat or recovered heat, but these systems are generally bulky and heavy. Thermoelectric air-conditioners are portable and low noise, but have relatively low COPs and are expensive. Furthermore, these systems operate using DC power, and so would need a DC power converter if powered by AC mains. However they could be powered directly by PV or fuel cells. [4]

Astrain et al (2005) [5] developed computational model, which simulates thermal and electric performance of thermoelectric refrigerators, had been developed. This model solves the non-linear system that is made up of the thermoelectric equations and the heat conduction equations providing values for temperature, electric consumption, heat flow and coefficient of performance of the refrigerator. FDM method is used in order to solve the system and also semi empirical expressions for convection coefficients. Subsequently a thermoelectric refrigerator with an inner volume of 55×10^{-3} m^3 has been designed and tested, whose cold system is composed of a Peltier pellet (50 W of maximum power) and a fan of 2 W. An experimental analysis of its performance in different conditions has been carried out with this prototype, which, in his turn, has been useful for assessing the accuracy of the developed model. The built thermoelectric refrigerator prototype, offers advantages with respect to vapor compression classical technology such as: a more ecological system, more silent and robust and more precise in the control of temperatures which make it suitable for camping vehicles, buses, special transports for electro medicine.[5]

Goktun et al (1992) [6] revives design methodology by considering irreversibility in thermoelectric module caused by electrical resistive losses. Defines new parameter called device design parameter which characterized both internal and external irreversibility. It has been shown that the internal and external irreversibility in a thermoelectric refrigerator can be characterized by a single parameter X, named the device-design parameter. This parameter appears in both the equation for optimum refrigeration effect and maximum input power. [6]

Jiajitsawat et al (2012) [7] performed work with objective of theoretically and experimentally investigate the feasibility of employing a thermoelectric refrigeration system to improve the air-cooling performance of a portable DEAC system. A portable hybrid thermoelectric-direct evaporative air cooling system has been fabricated and tested. A portable hybrid thermoelectric-direct evaporative air cooling system can improve the cooling performance of DEAC system by 10% & up to 20% with higher fan speed. 2.6 degrees of temperature drop. The concept of applying TE to cool the water is reliable and possible for commercial development. [7]

The main objective of this study is to configure hybrid refrigerator by introducing Peltier module (TER) in domestic refrigerator (VCR) & to study and analyze compressor cycles of conventional refrigerator i.e. VCR system. Comparison of standalone VCR and Hybrid VCR+TER system based on parameters selected.

II. EXPERIMENTATION

As per the objectives listed, first task is to configure the hybrid refrigerator by introducing Peltier module in domestic refrigerator. As shown in Figure 1 Peltier module is to be fixed on separator of freezer & cooler section in refrigerator. In this particular configuration, cold side of the module is inside the cooler compartment of refrigerator and hot side is exposed to atmosphere. Similarly, different configurations are to be made and tested simultaneously for better COP of the module. Seven thermocouples are to be placed according to the positions given in setup diagram.

Where,
T_1= Temperature of Compressor suction
T_2= Cabinet temperature.
T_3= after condenser
T_4= after expansion
T_5= Atmosphere temperature
T_6= Temperature of Freezer section
T_7= Temperature of Compressor discharge

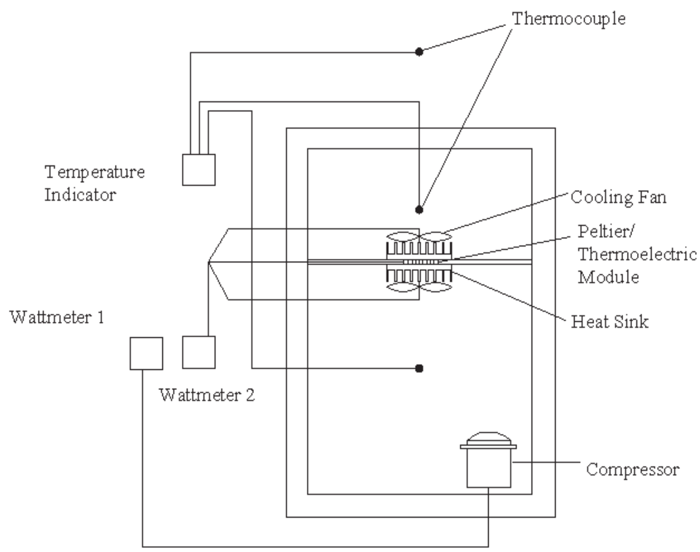

Figure 1 Schematic Diagram of Experimental setup (Front view)

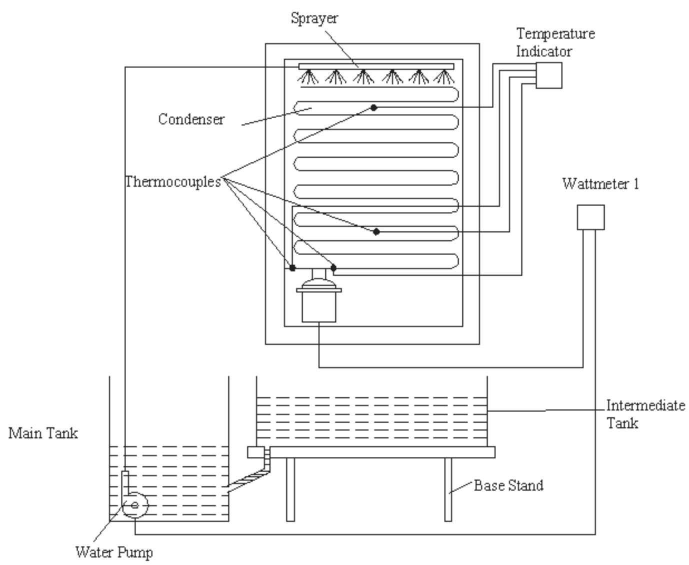

Figure 2 Schematic Diagram of Experimental setup (Back view)

To develop the setup for the experiment 2 configurations are taken into consideration:
Structure I: Cold side of the module is exposed to cooler compartment while hot side is placed in freezer compartment.
Structure II: Hot side is placed in cooler compartment & cold side is in freezer compartment.

In order to achieve above said objectives following procedure is followed and observations are taken:

A. Experimental Procedure

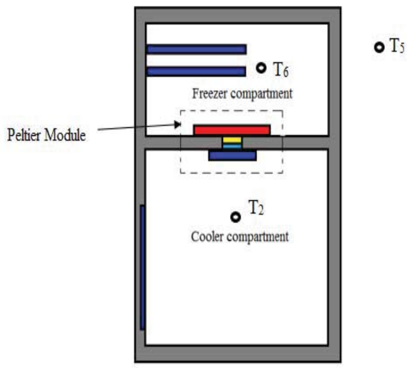

Figure 3 Experimental setup in Structure I

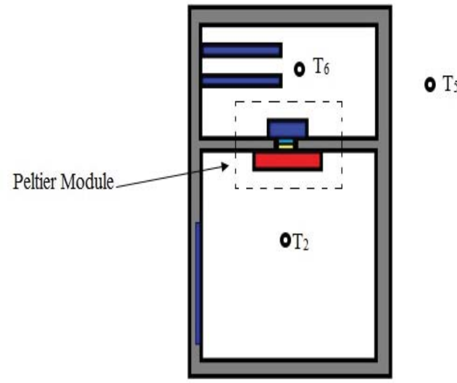

Figure 4 Experimental setup in Structure II

Experiment with standalone VCR

- Turned on the refrigerator & noted down the initial temperatures.
- Waited for compressor to trip for & noted down the time as well as corresponding temperatures.
- Then observed every trip cycle of the compressor & readings are recorded.
- Procedure is carried out for the span of 6 hours.

Similar procedure is carried out for experiment in combination with TER system in structure 1 & structure 2.

Some important terms

- Cyclic TER: Energy supplied to TE Module from start of the compressor
- Intermediate TER: TE module is kept on during trip time only.
- AC & WC: Air Cooled condenser & Water Cooled Condenser.
- Cyclic WC: Water pump is put on from start of the compressor.
- Intermediate WC: Water pump on during trip time only.

III. METHODOLOGY

a. Observations

- Compressor work input: 110 W
- TE module input: 20 W
- Water Pump input: 20 W

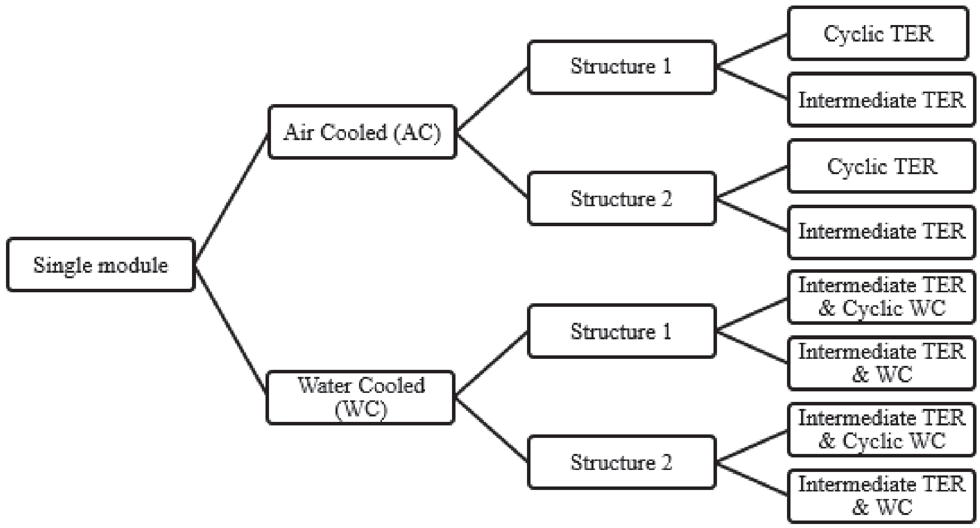

Figure 5 Experimentation methods for single TE module

b. Analyzing Energy Consumption

Energy consumption is determined by calculation of total run time for compressor, TE module & water pump. Energy consumed by these three devices is calculated in terms of units (KWh) for a period of 24 hours i.e. KWH/day.

Therefore, (For span of 6 hours)
Energy Consumed by Compressor/Day (E_{Comp}) = Compressor Input (KW) × Run Time (hours) × 4
Energy Consumed by TE Module/Day (E_{TE}) = TE Module Input (KW) × Run Time (hours) × 4
Energy Consumed by Water Pump/Day (E_{Pump}) = Water Pump Input (KW) × Run Time (hours) × 4

Total Energy Consumption = $E_{Comp} + E_{TE} + E_{Pump}$

c. Analyzing COP of hybrid system:

The coefficient of performance is determined from the P-H chart by plotting temperature & pressure values observed during experimentation. For this we assumed suction pressure of the compressor as 0.97 bar & discharge pressure is calculated from the formula of temperature ratios.

$$P_2 = P_1 \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

Using this equations & values of pressure & temperature we have plotted refrigeration cycle on P-H chart of R-12 refrigerant. Reading the corresponding enthalpy value, COP is calculated by the formula,

$$COP = \frac{h_1 - h_4}{h_2 - h_1}$$

Table 1 Result Table

Process	Comp Run Time (mins)	TER Run Time (mins)	Water Pump Run time (mins)	Total Energy Cons (units)KWh	Energy Cons/Day KWh	COP (From P-H Chart)
Normal VCR	282	0	0	0.517	2.068	2.095
Structure 1, CTER	293	360	0	0.657	2.629	2.224
Structure 1, ITER	266	94	0	0.519	2.076	2.327
Structure 2, CTER	283	360	0	0.639	2.555	2.630
Structure 2, ITER	247	113	0	0.491	1.962	2.641
Normal VCR, CWC	280	0	360	1.173	4.693	1.714
Structure 1, ITER & CWC	272	88	360	1.188	4.752	2.000
Structure 1, ITER & IWC	248	112	112	0.697	2.789	1.766
Structure 2, ITER & CWC	260	100	360	1.170	4.680	2.050
Structure 2, ITER & WC	236	124	124	0.701	2.805	1.800

IV. RESULTS & DISCUSSION

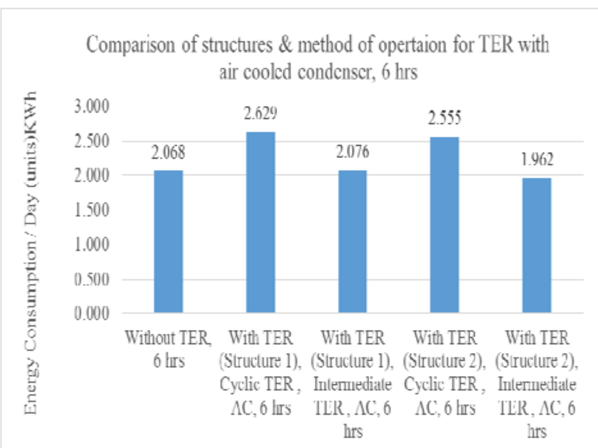

Figure 6 Energy Consumption with different methods with Air cooled

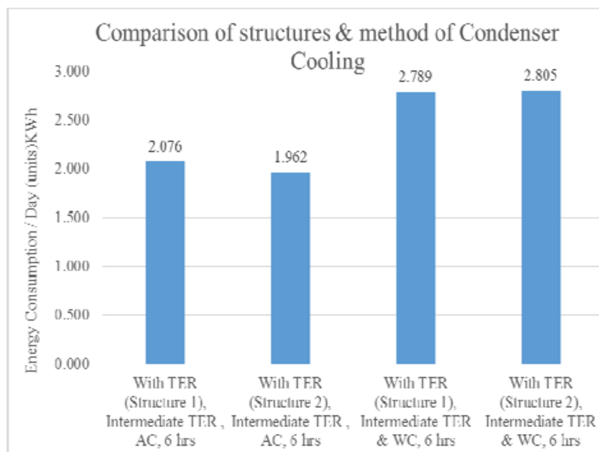

Figure 7 Comparison of Structures with Air cooled

Figure 6 shows the comparison of structures with different methods of experimentation for Air cooled condenser. Here Structure 2 with intermediate power supply gives better energy efficiency as it consumes 1.962 units per day compared to standalone VCR system which consumes 2.068 units. Structure 1 & cyclic power supply consumes more energy than even standalone VCR system.

Figure 7 shows the comparison of structures with different cooling method for condenser, in which again Structure 2 with intermediate power supply seems to be superior. In case of water cooled condenser pump consumes additional units of energy which leads to greater energy consumption.

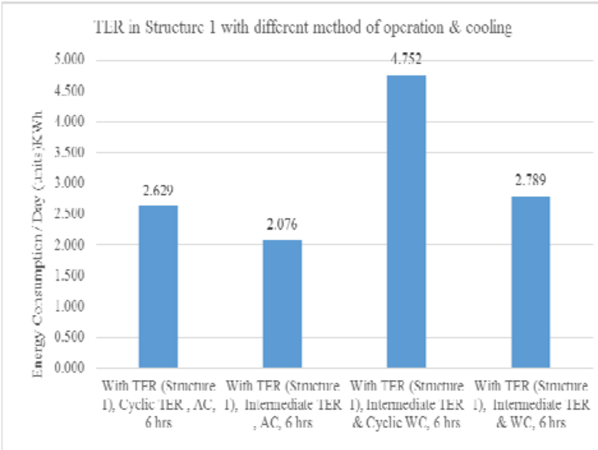

Figure 8 Energy consumption with Structure 1

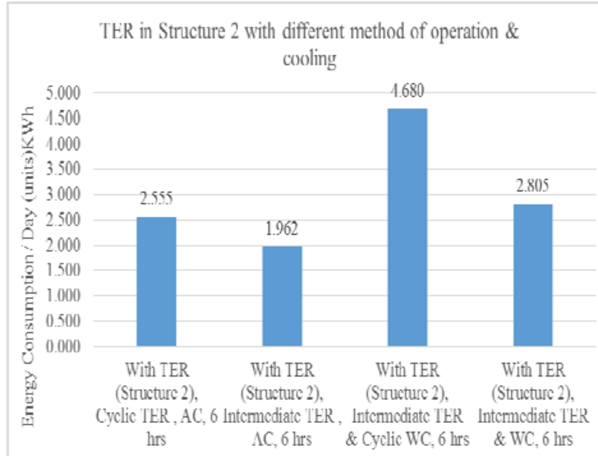

Figure 9 Energy consumption with Structure 2

Also Figure 8 & Figure 9 shows that intermediate supply to TER is efficient to reduce the energy consumption. Water cooled condenser doesn't have any useful impact on the energy efficiency of refrigerator.

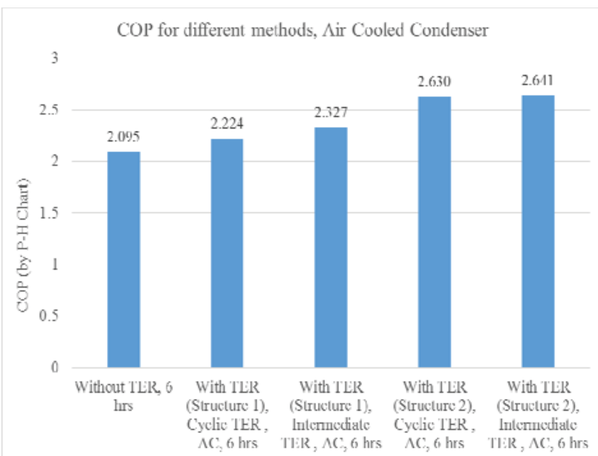

Figure 10 COP for different structures with Air Cooled condenser

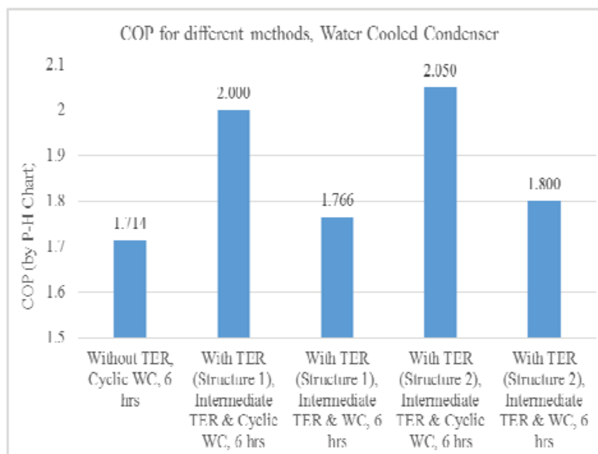

Figure 11 COP for different structures with Water Cooled condenser

Figure 10 & Figure 11 shows the COP variation in different methods of experimentation with Air ooled & Water cooled condenser. COP is calculated from the P-H chart & corresponding values of temperature & pressure. From both the graphs we can say that COP is incresed in case of TER with strructure 2 & intermediate supply.

V. CONCLUSION

Present study deals with hybrid refrigerator that combines thermoelectric (TER) and vapor compression refrigeration (VCR) and also entail experimental details of combined VCR & TER system. Comparison of standalone VCR and Hybrid VCR+TER system with air cooled & Water cooled condenser is carried out. A Peltier module of size 4cm×4cm×0.4cm is introduced in the refrigerator cabinet & the effect on energy efficiency in terms of trip time of compressor is recorded. The effect of Air cooled & Water cooled condenser with TER in different structures is also investigated.

It is observed that by introducing Peltier module during compressor trip time, run time of compressor is reduced. Out of two structures, structure 2 gives fairly good results. Using Peltier module in structure 2 intermediate supply & air cooled condenser, energy efficiency is increased up to 15.72% and almost 39 units of reduction per year compared to standalone VCR. As the refrigerator used for the experimentation is of old technology using R-12 as a refrigerant, reduction in consumed units can be increased up to 70-75 units per year in modern refrigerators. We can say that structure 2 with intermediate operation & air cooled condenser is best possible location of Peltier module in refrigerator.

The study of this paper also concludes that, to achieve better COP & temperature control we can combine TER with VCR systems. Hence it is better to have such hybrid systems & devices to reduce total energy consumption.

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