

# DEVELOPMENT AND TESTING OF A COMBINED REFRIGERATOR/HEAT PUMP AND GEYSER

JG Mukuna, M Kilfoil, M Heun  
Cape Peninsula University of Technology, Cape Town, South Africa

## ABSTRACT

To reduce the demand for electricity in South Africa, a combined refrigerator/heat pump and geyser is being developed. The condenser of a typical domestic refrigerator is a refrigerant-to-air heat exchanger. This condenser may be replaced by a specially designed refrigerant-to-water heat exchanger. The new system uses the heat energy rejected from the condenser of vapour-compression refrigerator to heat water in the geyser. With the evaporator in the refrigerator, the condenser in the geyser, and two stages of compression to reach a high condenser temperature, a water temperature of 55°C can be obtained whilst reducing the total energy consumption from the two systems (refrigerator and geyser).

The coefficient of performance ( $CoP$ ) of the system, the rate of the rejected heat at the condenser, and the time to heat water in the geyser are determined from a thermodynamic analysis of the system. To perform the analysis, the heat flow out of the geyser and the heat flow into the refrigerator from the surroundings are considered.

The results of thermodynamic analysis show that the combined refrigerator/heat pump and geyser is technically feasible.

## 1. INTRODUCTION

The National Energy Regulator of South Africa estimates that South African households consume about 17% of South Africa's electricity. Often, a home's single largest electricity expense is water heating, which typically accounts for about 40% of electricity usage. The total energy consumption by geysers will continue to increase as the population grows. As electricity demand increases, the adverse environmental effects and the economic costs associated with electricity generation will also increase [1].

Households need both refrigeration and water heating. Refrigeration at temperatures below 4°C is employed for food preservation, while hot water at temperatures around 55°C is used for bathing and showering. But it is common for refrigeration and water heating system to be separate and unconnected, each consuming the purchased energy. A more efficient use of this electrical energy would be to integrate the refrigeration and hot water systems. This

would reduce the electrical power consumed by heating water.

Considering this, the main objectives of the research project are:

- Produce and test a prototype of "combined refrigerator/heat pump and geyser".
- Determine the rate of heat that the refrigeration part of the combined system provides to the geyser under continuous and cycling operations.
- Evaluate the efficiency or the coefficient of performance of the combined system.
- Analyse system performance under different conditions.

This paper presents only the analytical development of the combined refrigerator/heat pump and geyser. Experiments will be performed later.

## 1.1. BACKGROUND

Both refrigerators and heat pumps move heat from a cold thermal reservoir to a warm thermal reservoir. The objective of refrigerators is to remove heat from a cold space whereas the objective of heat pumps is to put heat into a warm space [2]. Both heat pumps and refrigerators use the same thermodynamic cycle and principles.

When a household refrigerator is operating, it rejects heat into the environment at the condenser and in warm climates that heat is usually wasted. In this research, we are studying the feasibility of a new system which will use the rejected heat at the condenser of the refrigerator to heat water in the geyser. Thus, a combined refrigerator/heat pump and geyser results in a single machine which maintains a certain physical space at cold temperature for storage of food and uses the heat rejected by the refrigeration part for water heating.

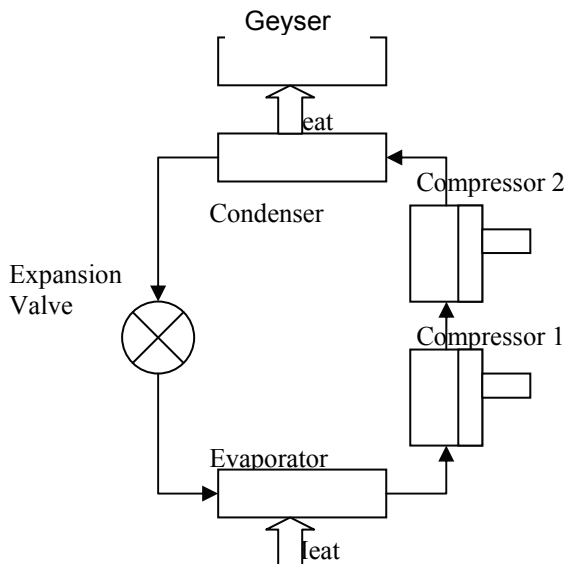


Figure 1: A combined vapor-compression refrigeration system and geyser

Figure 1 shows that a vapour compression cycle will be used with the evaporator in the refrigerator and condenser in the geyser. Cold and low pressure refrigerant gas enters the compressors where its pressure (and temperature) will be increased. After the compressors, it will then pass through the condenser where it will give up heat at approximately constant pressure to the water in the geyser so that the refrigerant's temperature decreases sufficiently for it to condense into a sub cooled liquid. After leaving the condenser it will go through an expansion valve (which may be a capillary tube). The decrease in pressure in the expansion process will cause the refrigerant to turn back into a mixture of liquid and vapor but at a much lower temperature. Then it will go to the evaporator where it absorbs heat at approximately constant pressure from the food in the refrigerator.

## 1.2 LITERATURE REVIEW

Almost nothing seems to have been published on this concept. Only one article was found on a combined system like the one proposed here [3]. In this article, O'Brien *et al.* presented a system that utilises the heat energy which is normally rejected from a refrigerator to heat the water for a home. The system is called the "Home Energy Centre (HEC). In the HEC system, the compressor and the condenser are placed in a polyethylene tank filled with water which becomes a heat sink for the waste heat energy from the refrigerator. After the experimentation, they concluded that the HEC system was able to recover 1700kJ more energy for the time of the test. On the other hand, the condenser rejected only 10 % of its available energy to the heat sink. Therefore; their system was not able to deliver the expected energy recovery from the refrigeration waste heat.

Apart from this single reference, we found that most researchers are focused on combined systems using an adsorption cycle. A recent review of literature [4] lists 76 other articles with adsorption cycles creating refrigerating effect. There has also been important work in the area of

heat pumps, using a vapour compression cycle for water heating, for example [5]-[7]. However low temperatures created by the evaporator side of the cycle were not exploited.

## 1.3 RESEARCH QUESTIONS

O'Brien *et al.* worked in New Zealand and showed that the combined system is technically feasible. In this study we aim to answer the following questions:

- Do we need an electrical assist heater in the geyser?
- Under continuous operation of the refrigerator, will we overheat the geyser? Or comprise the refrigerator's effectiveness?
- Do we need an air-cooled condenser attached to the fridge?

## 2. METHODOLOGY

To respond to these questions, a thermodynamic model of the combined system has been developed using an Excel spreadsheet.

### 2.1 THERMODYNAMIC ANALYSIS

Initial design choices are based on typical temperatures and, as far as possible; the design will be based on locally available domestic refrigerators, geysers, and refrigerants. Therefore we are modeling a refrigerator with a capacity of 300L and a geyser with a capacity of 150L, and R134a.

As the maximum water temperature in the geyser needs to be 55°C, the saturation temperature of refrigerant of the refrigerant in the condenser can be approximately 70°C. With an evaporator temperature of -5°C, different values of state variables for each stage of the combined refrigerator/heat pump and geyser can be read on the pressure enthalpy diagram or on the thermodynamic tables of refrigerant R134a.

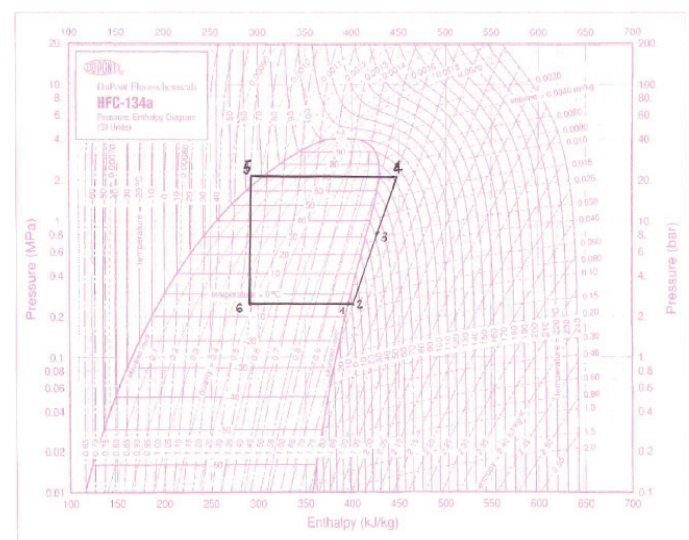


Figure 2: Cycle diagram of the combined system

For reciprocating compressors the maximum compression ratio “r” for a single-stage unit is about 7. The volumetric efficiency of a typical reciprocating compressor  $\eta_v$  decreases from 0.92 to 0.65 when r increases from 1 to 6, and the isentropic efficiency  $\eta_{isen}$  decreases from 0.83 to 0.75 when r increases from 4 to 6 [8]. From the cycle diagram, the evaporator pressure is 2.46 bars and the condenser pressure is 21.17 bars, and the compression ratio for the combined system is 8.6, too large for single stage compression. Therefore two compression stages are needed.

We investigated combinations of different modes of operation for the refrigerator and the geyser.

Table 1: Combinations of modes of operation between the refrigerator and the geyser

		refrigerator	
		( Rco)	( Rcy)
Geysers	(Gco)	Rco –Gco	Rcy –Gco
	(Gcy)	Rco –Gcy	Rcy –Gcy

Concerning geysers, two modes of operation are commonly observed:

- Cycling on and off to keep the water in the geyser at the set point temperature. This is the normal mode when no or very little hot water is being used (Gcy). In this mode, the geyser heater overcomes “standing losses.”
- Continuous heating for anything from half an hour to two hours after a large amount of hot water has been tapped out of the geyser (Gco).

Refrigerators have a cycling mode and (Rcy) continuous cooling mode of operation (Rco), too. The cycling mode keeps the food products in the refrigerator cold compensating for the heat leak through the walls of the fridge whereas the continuous cooling occurs when large amounts of warm or room temperature food products are placed in the refrigerator.

### 2.1.1 Continuous mode of refrigerator

To assess to continuous mode of refrigerator operation, we have considered an affordable capacity of a typical refrigerator as 250 liters; the maximum heat to be removed from the food in the refrigerator can be calculated by using the following formula:

$$Q_{ev} = mc (T_o - T_i) \quad (1)$$

With  $Q_{ev}$  = heat leak into the refrigerator

m= mass of food in the refrigerator

c =specific heat of food (assumed to equal the Specific heat of water).

$T_o$  = evaporator temperature

$T_i$  = room temperature

Considering 120 liters of room-temperature food added to the refrigerator compartment, evaporator temperature  $T_{ev} = -5^\circ\text{C}$ , room temperature  $T_i = 20$  and specific heat of the food equal to specific heat of water  $c = 4.18\text{kJ/kg.K}$  [1], the heat removed to cool the food in the continuous operation of the refrigerator  $Q_{ev} = 11536.8$  kJ. For required cooling time of 2h 30min, with a difference of enthalpy of 110kJ/kg as read on the cycle diagram, this analysis shows that we need a refrigerant mass flow rate

$\dot{m} = 0.01165$  kg/sec and a heat removal rate at the evaporator of 1.28 kW.

And the rate of rejected heat at the condenser is 1.89 kW with a difference of enthalpy equal 162.85 kJ/kg.K.

### 2.1.2 Cycling mode of the refrigerator

For this mode of operation, the heat removal rate at the evaporator is found by considering the heat leak through the walls of the fridge.

It was calculated by analyzing the conduction between the air-room and the cooled space.

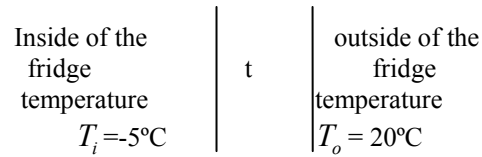


Figure 3: Heat transfer through the wall of the fridge

With a thickness of insulation t estimated to 0.5dm, an outside area of the fridge  $A_o = 432\text{dm}^2$  and an inside area  $A_i = 275\text{dm}^2$ , the rate of heat leak through walls is given by the following formula:

$$\dot{Q} = (T_o - T_i) / (1/h_o \cdot A_o + t/k_i \cdot A + 1/h_i \cdot A_i) \quad (2)$$

With  $h_o$  : the outer convective heat transfer coefficient.

$k_i$  : the thermal conductivity of the insulation

$h_i$  : the inner convective heat transfer coefficient

$$A = (A_o + A_i)/2$$

Assuming relatively quiet air surrounding the refrigerator and in the food compartment, we estimate the heat transfer coefficients to be  $h_o = 12$  W/m .K,  $h_i = 8$  W/m .K.

If we assume polystyrene insulation is used in the refrigerator walls, we have and  $k_i = 0.03$  W/m.K [9], and the rate of heat leak into the fridge is 0.037kW. With this amount of rate of heat and the mass flow rate of refrigerant is 0.01165 kg/sec, and the rate of rejected heat at the condenser is 0.051 kW.

### 2.1.3 Continuous mode of the geyser

For this mode, a 150L geyser has been considered for the study because it is almost used in households in South Africa [10]. For the calculations we have considered a geyser with a standing loss per day equals to 2.3 kWh [10].

If the tap water temperature is 15°C and the standing temperature in the geyser is 55°C, the total energy to heat water is given by the equation (1)

With:  $m$  = mass of water in the geyser  
 $c$  = specific heat of water  
 $T_o$  = hot water temperature (55°C)  
 $T_i$  = cold water temperature (15°C)

For a heating time requirement of 2.5 hours, the required rate of heat in the geyser is 2.57 kW.

### 2.1.4 Cycling mode of the geyser

During cycling mode, the geyser overcomes standing losses. For this study a standing loss of 2.3 kWh per day (or 0.0958kW) is considered.

Table 2 shows the summary of these analyses.

Table 2: Heat rates of the refrigerator and geyser for different modes of operation

	Fridge: $Q_{evap}$ [kW]	Fridge $Q_{cond}$ [kW]	Geysers: $Q_{heating}$ [kW]
Continuous mode	1.28	1.89	2.57
Cycling mode	0.037	0.051	0.095

### 2.1.5 Coefficient of performance

To close this analysis, we have calculated the coefficient of performance of the system.

We have defined the coefficient of performance of the combined system as the sum of the coefficient of performance of the refrigerating effect plus the coefficient of performance of the heat pumping effect.

$$CoP = (Q_{evap} + Q_{cond}) / W_{comp} \quad (3)$$

With the coefficient of performance of the refrigerating effect defined as:

$$CoP_r = Q_{evap} / W_{comp} \quad (4)$$

the coefficient of performance of the heat pumping effect defined as:

$$CoP_{hp} = Q_{cond} / W_{comp} \quad (5)$$

and  $Q_{cond} = Q_{evap} + W_{comp}$ , the coefficient of performance of the combined system is:

$$CoP = 2 CoP_r + 1 \quad (6)$$

With  $Q_{evap}$  = rate of removed heat in the refrigerator

$Q_{cond}$  = rate of rejected heat at the condenser

The  $CoP$  of the combined system is 6.52 with a  $CoP_r = 2.76$ .

## 2.2 DESIGN IMPLICATIONS

1. Will standard refrigerator compressors work for the combined system?

As the maximum hot water temperature is 55°C, the condenser temperature after sub cooling must be at least 65°C. Hence the refrigerant sub cooling at the exit of the condenser is 5 °C. For that, the

calculated mass flow rate is  $m = 0.01165$ kg/sec and the swept volume of the compressor is 26.17 cm<sup>3</sup>/rot. This is too big for refrigerator compressors. The available compressors for fridge in South Africa provide a swept volume of 10 cm<sup>3</sup>/rot. So, two larger compressors will be required. To reduce the swept volume of compressors, a sub cooling of 15 °C is required.

To answer the remaining design questions, a table of mismatch heat between geyser and refrigerator for different modes of operation is given below.

Table 3: Mismatch of rate of heat for different modes of operation (( $Q_{required, geyser} - Q_{cond}$ ))

	( $R_{co}$ )	( $R_{cy}$ )
( $G_{co}$ )	0.68kW	2.51 kW
( $G_{cy}$ )	-0.245 kW	0.044 kW

2. Is a supplemental condenser required?

For the combination  $R_{co}-G_{cy}$ , the difference is less than zero; then heat rejected at the condenser is higher thus the rate of heat needed in the geyser. We will overheat the water in the geyser. To ensure a reasonable successful operation of the system, a supplementary condenser will be needed on the refrigerator.

3. Is an electrical assist heater needed in the geyser?

For the combination  $R_{cy}-G_{co}$ , the mismatch between geyser heat required and condenser heat

supplied is too big. Thus, an electrical assist heater is needed.

For the combinations Rco-Gco and Rcy-Gco, the mismatch is small and the electrical assist heater is not necessary.

### 3. CONCLUSION

The thermodynamic analysis shows that the combined refrigerator and geyser can be feasible. But, significant changes in the design of the refrigerator will be required, including, two-stage compression, larger compressors, and an additional refrigerant-to-water heat exchanger.

As both refrigerators and geysers can work in continuous or cycling mode, all four combinations have been considered.

For a full load operation of the refrigerator and full load operation of the geyser the mismatch on the rates of heat is 0.83kW to heat water from 15°C to 55°C. For the cycling mode of operation of the both, the mismatch is 0.044kW. But cycling mode on the geyser and continuous mode in the refrigerator will result in overheating the water. To ensure a good working of the compressors a supplementary condenser will be needed.

The cycling mode in the refrigerator and continuous mode in the geyser result in a very slow heating of water in the geyser. Hence a supplementary electric heating element in the geyser will be needed.

To reach refrigerant sub cooling of 15 °C, a supplemental air condenser is needed. This is a repeat of a previous conclusion statement.

### 4. REFERENCES

- [1] South Africa. Department of Minerals and Energy, Energy efficiency strategy of the Republic of South Africa. Pretoria, March 2005.
- [2] Yunus A. Cengel & Michael A. Boles. *Thermodynamics, an engineering approach*, 4<sup>th</sup> edition. New York, NY: Mc Graw Hill, 2002
- [3] O'Brien JM, Bansal PK. and Raine RR. An integrated domestic refrigerator and hot water system. *International Journal of Energy Research*. Vol 22, N°8, June 1998, pp. 761-776.
- [4] Alghoul MA, Sulaiman MY, Azmi BZ and Wahad MAdb. 2007. Advances on Multi-Purpose Solar Adsorption Systems for Domestic Refrigeration and Water Heating, *Applied Thermal Engineering*. Vol 27, N°5, April 2007, pp. 813-822.
- [5] Kim M, Kim MS and Chung JD. Transient thermal behaviour of water heater system driven by a heat pump. *International Journal of Refrigeration*. Vol 27, N°4 April 2004, pp. 415-421.
- [6] Shao S, Shi W, Li X and Ma J. A new inverter heat pump operated all year round with domestic hot water, *Energy Conversion and Management*. Vol 45, N°13, August 2004, pp. 2255-2268.
- [7] Zhang J, Wang RZ and Wu JY. System Optimization and Experimental Research on Air source Heat Pump Water Heater, *Applied Thermal Engineering*. Vol 27, N° 5-6, April 2007, pp. 1029-1035
- [8] Shan K. Wang. *Handbook of Air Conditioning and refrigeration*, 2<sup>nd</sup> edition. New York: Mc Graw-Hill, 2001.
- [9] J H. Lienhard IV and J H. Lienhard V. *A heat transfer textbook*, 3<sup>rd</sup> edition. Cambridge: Phlogiston, 2008.
- [10] A. Harris, M. Kilfoil and E-A Uken, Domestic Energy savings with Geyser Blanket. Proceedings of 14<sup>th</sup> International Domestic Use of Energy Conference. Cape Town, 2007.

### 5. AUTHORS

**Principal Author:** Jean Gad Mukuna Mubala holds a BEng degree in Mechanics and is currently busy with his MTech at CPUT.



**Co-author:** Mark Kilfoil, Pr Eng, Msc, Bsc, Bcom, HDET is lecturer in Mechanical Engineering at CPUT and previously at the University of Johannesburg. He has also worked for a mining equipment Company.



**Co-author:** Matthew K. Heun holds Ph.D. and M.S. degrees in Mechanical Engineering from the University of Illinois, USA. He holds a BS Engineering degree from Calvin College in Grand Rapids, Michigan, USA. He is a professor of engineering (mechanical concentration) at Calvin College.



**Presenter:** The paper is presented by Jean Gad Mukuna Mubala.

