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AN INTEGRATED DOMESTIC REFRIGERATOR AND HOT WATER SYSTEM

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SUMMARY

This paper presents a new design of a prototype refrigeration-cum-hot water heating system for domestic use. The system uses the heat energy rejected from the compressor and condenser of a vapour-compression refrigerator by storing it in a heat sink. This energy is then transferred to mains water entering the hot water cylinder, where the water temperature is boosted by an electric resistance heater to a preset temperature for domestic usage. A prototype system of such a configuration was assembled as an integrated unit with the refrigerator adjacent to the water tank. The system is called the Home Energy Centre (HEC). Power consumption and temperature distribution were measured for standing and draw off tests using the unit as a conventional hot water cylinder, refrigerator or as the combined system. A new parameter, ϕ, is defined to compare the system performance as the HEC prototype against its performance when working only as a refrigerator or a water heater. The system performed better as the prototype than it did as a hot water heater, but needs to be improved further to fully explore its expected potential. © 1998 John Wiley & Sons, Ltd.

KEY WORDS refrigerator; water heater; energy efficiency; heating; cooling

1. INTRODUCTION

Domestic hot water heating in the 1·3 million dwellings (Cook, 1996) of New Zealand accounted for nearly 20% of national electrical power consumption (EECA, 1994) in 1996. This energy amounts approximately to 6·1 TWh (EDF, 1996), and will continue to increase as the population grows. As New Zealand's electricity demand increases, the adverse environmental effects and the economic costs associated with electricity generation will also increase. These effects include increased carbon dioxide emissions, and the degradation of environment quality as more rivers are dammed for hydro power schemes. It has to be remembered that New Zealand has commitments to reduce greenhouse gas emissions under international agreements, as recommended by the Rio Convention on Climate Change. In addition to this, energy resources are scarce and should be conserved whenever possible.

When considering energy conservation it is important to consider the conservation of both the energy quantity and quality. Awareness of the need to conserve energy quantity is high, but the need to conserve energy quality in not. It is vital that the use of energy is analysed based on both the First and Second Laws of Thermodynamics. Thus, when considering the heating of water using electricity, the process is wasteful from a Second Law viewpoint, because of a lack of energy quality conservation. The electricity supplied to the element is high-quality energy that can be easily converted to work. However, when it is used to heat the water in a hot water cylinder, this high-quality electrical energy is degraded to low-grade thermal energy. At the same time as this high-quality energy is downgraded, a low-grade thermal energy source, the heat removed from the refrigerated space of domestic refrigerators is wasted/rejected to the environment.

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Obviously, an ideal use of this thermal energy would be to heat the hot water required in the home. This would mean more efficient use of the energy consumed in refrigeration and reduced electrical power demands from hot water heaters.

This paper presents a novel system that utilises the heat energy which is normally rejected from a refrigerator to heat the water for a home, with the aim of achieving better energy efficiency from such a combined system. The system is called the Home Energy Centre (HEC) as shown in Figure 1. In the HEC system, the compressor and the condenser are placed in a polyethylene tank filled with water which becomes a heat sink (HS) for the waste heat energy from the refrigerator. Mains water entering the hot water cylinder

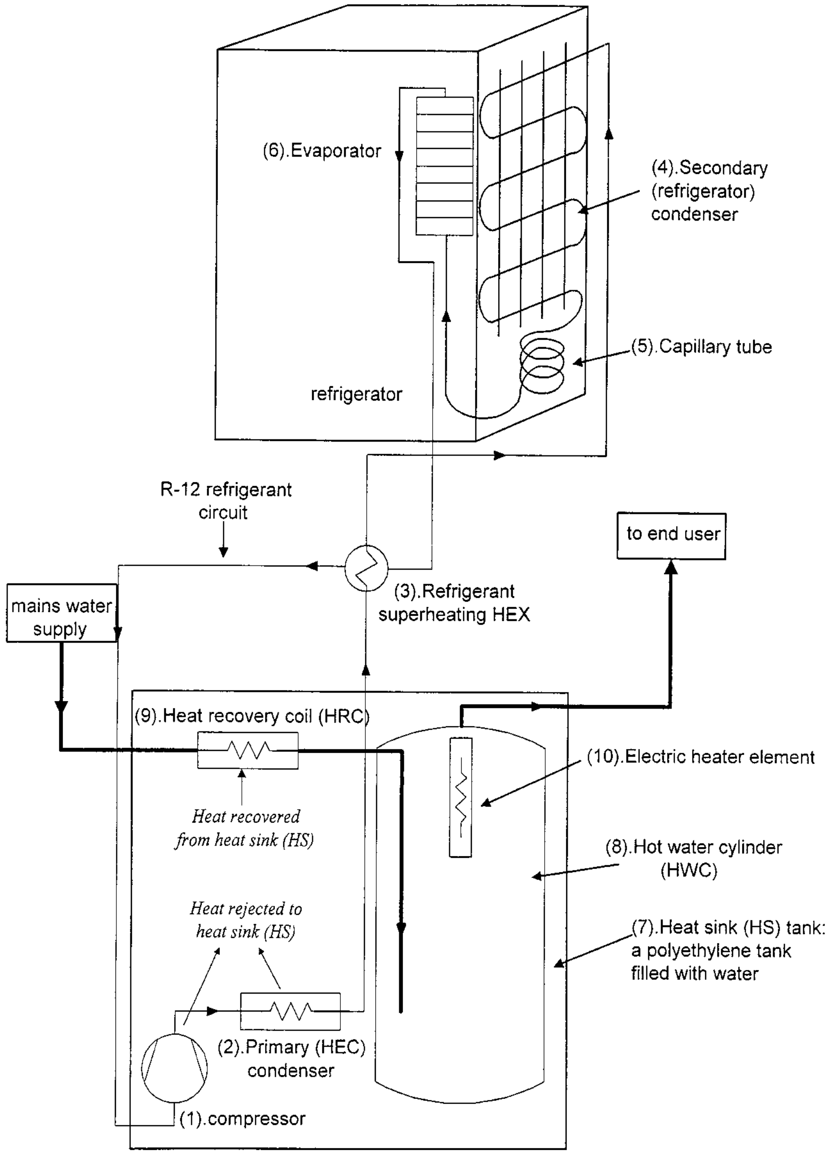

Figure 1. Schematic of the Home Energy Centre (HEC) system.

(HWC) is preheated by this stored energy. This preheating should then reduce the energy required to boost the water to end use temperatures. This paper covers the theory on the HEC unit, and describes the analysis methods used to evaluate the concept.

2. SYSTEM DESCRIPTION

The theory of refrigeration is covered by many textbooks on thermodynamics e.g. Cengel and Boles (1994). The theory of the HEC system is presented here and the concept of an appropriate coefficient of performance (COP) is introduced.

2.1. Principles of operation

The basic layout of the HEC system is shown in Figure 1. The major components of the system are indicated and include the: (1) compressor, (2) primary (HEC) condenser, (3) refrigerant superheating heat exchanger (HEX), (4) secondary (refrigerator) condenser, (5) capillary tube, (6) refrigerator evaporator, (7) heat sink (HS) tank (a polyethylene tank filled with water), (8) hot water refrigerator evaporator, (7) heat sink (HS) tank (a polyethylene tank filled with water), (8) hot water cylinder (HWC), (9) heat recovery coil (HRC) and (10) electric resistance-type heater.

The waste heat energy comes from the (1) compressor and the (2) primary condenser. The primary condenser rejects the heat removed from the refrigerated space to the HS (7). It is placed immediately after the compressor in the cycle so that the refrigerant is at the highest temperatures. The heat energy from both of these sources is stored in the HS. This energy is then recovered from the HS using the (9) heat recovery coil (HRC), a copper tube acting as a heat exchanger. Mains water enters the HRC, flows though it and absorbs heat energy from the HS, before leaving the coil and entering the HWC at the bottom. The heated water is stored in the HWC and is boosted by a two-kilowatt electric element to end use temperatures.

In addition, there are several other features of the system.

- A section of the original refrigerator condenser (4) is retained as the secondary condenser to ensure full condensation of the refrigerant.
- A heat exchanger (3) is placed at the suction of the compressor to ensure that the refrigerant is superheated before entering the compressor. This prevents any two phase flow from entering the compressor. This heat exchanger (superheating HEX-3) transfers heat from the discharged refrigerant leaving the primary condenser (2) to the suction refrigerant at 3.

2.2 Energy sources

(1) *Compressor*: The HEC concept proposes to capture heat energy generated by the compressor in a heat sink and use it to heat water. The compressor is housed at the bottom of the HEC and HS assembly in a container filled with dielectric oil. Any heat energy generated is utilised to heat the oil, where from it dissipates into water in the HS tank.

(2) *Condenser*: In the HEC design, there are two condensers. The primary condenser is a copper tube that sits on the bottom of the HS tank on a stand and rejects heat energy to the HS water, instead of to the surroundings. This is where the greatest potential of the energy input from the refrigeration process can be capitalized by condensing the refrigerant from a super heated vapour to a sub cooled liquid. With a COP of one, modern refrigerators could reject over 100 W to the HS. The secondary condenser is the original refrigerator condenser. It still sits as its original position to accomplish cooling in situations when high temperatures in the HS are attained (e.g. during the holiday period when no water is drawn from the tank). This secondary condenser ensures that the refrigerant is a saturated liquid before entering the capillary tube.

2.3 Coefficient of performance

Figure 2 summarizes the objectives of the HEC design compared to the conventional refrigerator design. The net work input to the compressor, $W_{net, in}$ can be measured using the voltage and current drawn by the compressor. Q_L can be determined from enthalpy calculations based on measured pressures and temperatures. The energy recovered by the HEC design is the energy used to preheat the water. The wasted heat, Q_H, rejected to the surroundings, can be calculated similar to Q_L, using temperature and pressure to find enthalpy changes.

The coefficient of performance of the conventional refrigerator and HEC, based on the energy flows in Figure 2 are given by

$$COP_R = \frac{Q_L}{W_{net, in}} \tag{1}$$

$$COP_{HEC} = \frac{Q_L + Q_{HEC}}{W_{net, in}} \tag{2}$$

3. EXPERIMENTAL PROCEDURE

3.1. Testing methods

Two types of data were collected during the testing of the HEC unit. The first was the power consumed by the system, measured using a kilowatt hour meter. The element in the hot water heater and the compressor of

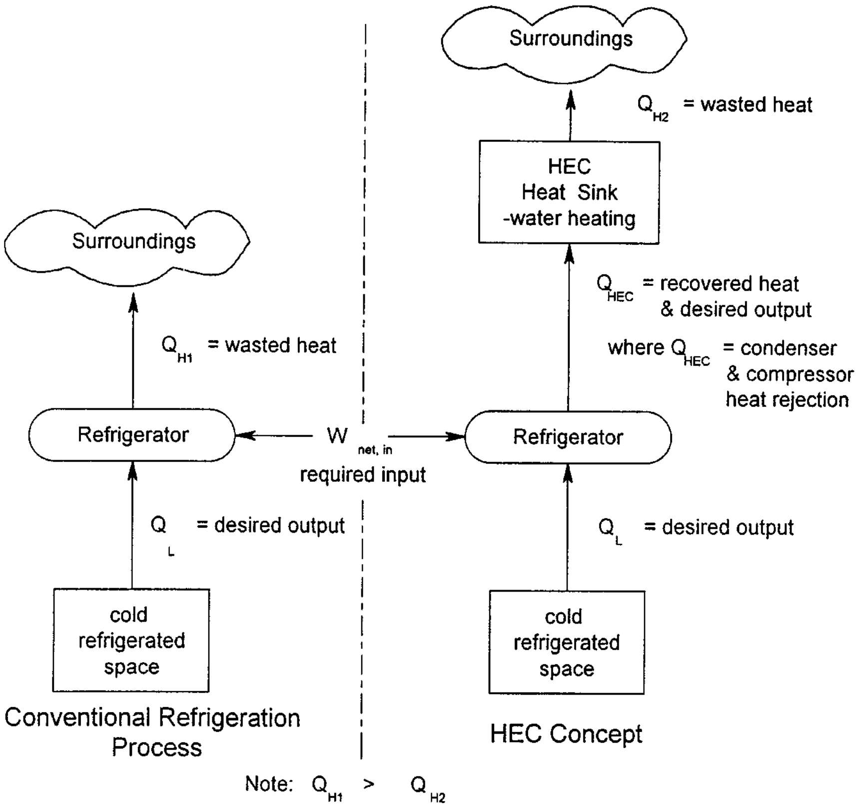

Figure 2. Comparison of Objectives of Refrigeration Process and HEC concept.

the refrigerator were both connected to kilowatt hour meters and comparisons were made among power consumptions in different configurations. The second type of data consisted of the temperatures at different locations within the system. The temperatures were measured using T type thermocouples, calibrated using ice water and boiling water baths to determine correction factors. The temperatures were measured every 5 min using a data logging system. The thermocouples were placed or attached to the test rig using insulated pockets. The locations of the thermocouples were the mains water in, HRC out, HWC outlet, HWC (3 points) HS (5), refrigerator interior, compressor discharge, primary condenser out, secondary condenser out, evaporator, compressor suction and the compressor oil. Additional points were also measured as required. The temperatures were used to carry out a heat transfer analysis of components in the system. A series of six tests were designed to collect this data, based on the Australian and New Zealand standards for hot water cylinder testing (Standards Association of New Zealand, 1991; Standards Australia, 1995)

3.1.1. Test procedures. The basic procedure for all the testing was the same. The unit was operated for 24 h to reach steady state before the testing was commenced. Six different configurations were used, as described below.

(1) *Heater standing loss test*: In this test, the unit was operated solely as a hot water cylinder with the refrigerator turned off, and the only power input was from the element. In this test there was no water draw off, so that any power consumed in heating would only be used to recover standing losses. In accordance with standards, the unit was also isolated from the mains supply and the outlet of the HWC.
(2) *Refrigerator standing test*: In this test, the performance of the refrigerator was studied and the HEC unit was modified to make it as close to a normal refrigerator as possible. The HS and the HWC were emptied and filled with cold mains water. In order to raise the level of refrigerator operation a load was placed in the refrigerator. This was accomplished using a light bulb delivering 30 W. This load was maintained for all the testing configurations involving the refrigerator.
(3) *HEC standing loss test*: In this test, the system was in the HEC configuration with both the element and the refrigerator running, but no draw off. This test was identical to the heater standing loss test, except that the refrigerator was also operating.
(4) *Heater draw-off test*: This test established the recovery characteristics of the system when it was operated purely as a hot water heater. The configuration was the same as for the heater standing loss test, type 1. Three water draw offs were made; 6·25 l or an eighth of the tank volume, a quarter or 12·5 and 25 l or half of the tank volume. Between draws during the tests the system was allowed some time to recover. The system was deemed to have recovered when the electric element heating the water in the HWC switched off after the water draw-off.
(5) *HEC draw-off test*: This test determined the recovery characteristics of the HEC unit when the system was in the same configuration as the HEC standing loss test, type 3. The draw offs were made in the same manner as the heater draw off test.
(6) *Refrigerator input test*: This test was conducted to determine the primary condenser (2) input when the heat sink was empty of water, and the element in the HWC was not operating. This test is a replica of test 2, but with the HS water drained. The goal was to determine whether the primary condenser in the HS was capable of condensing the refrigerant when the condenser was situated in air, as a normal refrigerator condenser.

These testing configurations are summarized in Table 1.

3.1.2. Power consumption test procedures. This series of tests recorded the difference between the initial and final readings on the kilowatt hour meters that measured the power consumed by the compressor and the HWC element. The difference was the energy input to the system, which enabled the calculation of standing losses from the system, because at steady state any energy input would be to compensate the standing losses.

3.1.3. Temperature distribution test procedures. This test was usually run in parallel with the power consumption test and measured temperatures in the system to calculate energy transfer. The duration of these tests was intended to be 24 h but this duration resulted in large volumes of data. The steady ambient conditions and the cyclic nature of the system enabled the duration to be reduced to a more manageable six hours.

4. ANALYSIS METHODS

The two types of data from the testing were treated in different ways. The power consumption figures were used to compare the HEC system to the benchmark systems, the refrigerator and the HWC. The power consumption and temperature distribution data were then used to interpret the system dynamics. The temperature data also enabled the estimation of the heat transfer and energy recovery within the system.

4.1. Power consumption data analysis

The testing types 1 and 2 represent a close approximation of a normal HWC and a refrigerator, respectively. The performance of the HEC system is then compared to these benchmark test types. The power consumed by the HEC system can be calculated as a fraction of these figures to yield a power consumption or efficiency comparison ϕ as

$$\phi = \frac{\text{Power consumed by HEC system}}{\text{Benchmark power consumption ie refrigerator or HWC test}} \tag{3}$$

When comparing the HEC performance to a normal HWC, the power consumed by the heating element is the relevant operational data. When the HEC system is compared to a normal refrigerator, the power consumed by the compressor in the testing is used. A ϕ less than one in either test indicated reduced power consumption in the HEC configuration.

4.2. Heat transfer analysis

The methods used to calculate heat transfer from the refrigerant condensing in the primary condenser as well the rate of heat flow from the compressor are introduced below. In addition, the heat transfer calculations for the HRC are also presented.

4.2.1. Refrigerator heat transfer. The energy rejected by the refrigerant was calculated using the energy transport equation:

$$\dot{Q}_{R} = \dot{m}_{R-12} \Delta h_{R-12} \tag{4}$$

Table 1. Summary of testing configurations

Test type	Element operating	Refrigerator operating	Water drawn off	Water in HS tank
(1) Heater standing loss test	Y	—	—	Y
(2) Refrigerator standing test	—	Y	—	Y
(3) HEC standing loss test	Y	Y	—	Y
(4) Heater draw-off test	Y	—	Y	Y
(5) HEC draw-off test	Y	Y	Y	Y
(6) Refrigerator input test	—	Y	—	—

The mass flow rate of the refrigerant was estimated from the swept volume and steady-state speed of the compressor (rpm) as

$$\dot{m}_{R-12} = \left(\frac{\dot{V} \cdot N}{v}\right)\eta_{vol} \tag{5}$$

where η_{vol} was assumed to be constant at 65%.

The heat rate from the primary condenser $\dot{Q}_{PC}$ can then be calculated using equation (4) as

$$\dot{Q}_{PC} = \dot{m}_{R-12}\,[h(T_{Discharge}) - h(T_{PC_{out}})] \tag{6}$$

where $T_{Discharge}$ is the refrigerant discharge temperature from the compressor, and $T_{PC_{out}}$ is the temperature of the refrigerant leaving the primary condenser. Similar calculations could be made for the energy rejected by the refrigerator condenser.

To analyse the energy recovered from the compressor, resistance analogy methods were used. The energy from the compressor enters the heat sink largely by conduction through the shell wall in which it is immersed. The heat transfer can be calculated using overall heat transfer coefficients, area and temperatures in the system.

To enable a more accurate analysis of the heat transfer from the compressor to the HS tank, the HS tank was divided into a series of nodes. The nodes are fully mixed regions with uniform properties throughout. This method of analysis has been used previously by Kleinbach *et al.* (1993) to model solar thermosyphons. The nodal analysis allows for a more realistic representation of the system by using more data points to describe the temperatures in it, rather than single average values for large components. The compressor shell, node C, is positioned in nodes 1 and 2 of the HS and rejects heat to both the nodes as shown in Figure 3. Therefore, two equations are required to describe heat transfer from the compressor shell to the HS, one for each node.

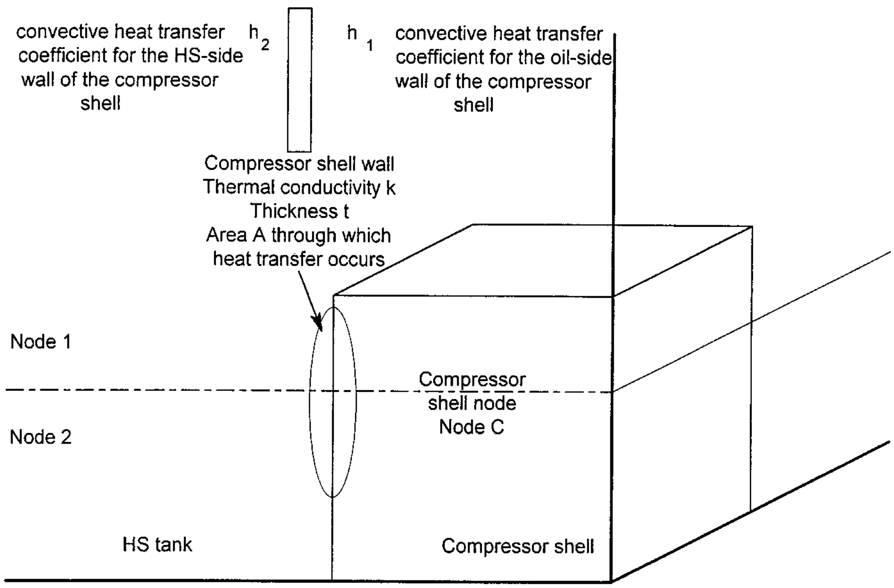

Figure 3. Schematic of model used for compressor heat transfer analysis.

Following the analogy of Figure 3, the overall heat transfer coefficient can be calculated using the resistance network as

$$\frac{1}{UA} = \frac{1}{h_1 A} + \frac{t}{kA} + \frac{1}{h_2 A} \tag{7}$$

where the convective heat transfer coefficients h_1 and h_2 are estimated based on the measured temperatures of the compressor oil and water, respectively. The equation for the heat transfer is from each node is then

$$\dot{Q}_{\text{comp}} = UA\,\Delta T \tag{8}$$

where ΔT is the measured temperature difference between the compressor shell and the HS. The two heat transfer rates are then summed to give a total heat transfer from the compressor shell.

4.2.2. HRC heat transfer analysis. The energy recovered by the water in the HRC was calculated using equation (9) after measuring the average temperature rise, ΔT, of the water from the mains inlet to the HRC exit. The flow rate of the water was measured prior to testing and held constant for the testing duration.

$$\dot{Q}_{\text{HRC}} = \dot{m}_{H_2O}\, C_p\, \Delta T \tag{9}$$

A mass flow rate of water was calculated from the measured volume flow rate and density and was found to be 0·075 kg s^{-1}. Equation (9) was then used to calculate the heat transfer. The product of this heat flow rate and the duration of the draw enabled the total energy transferred or recovered as

$$E_{\text{recovered}} = \dot{Q} \times \text{draw off duration} \tag{10}$$

5. EXPERIMENTAL RESULTS AND ANALYSIS

Several methods have been used to study the data gathered in testing and for interpreting the results. The different methods produce different perspectives on the data.

5.1. Kilowatt hour meters

The data gathered enables the calculation of power consumed in the testing configurations. The power used by the compressor and the HWC element of the HEC system can then be compared to the power usage of the normal systems. The normal systems, (test types 1 and 2) are used as benchmarks against which to compare the HEC system performance. The results are presented in Figure 4. The testing demonstrated that the HWC losses were reduced for the HEC system ie. 1·77 kWh in test 1a goes down to 0·91 kWh in test 3b; yielding an overall decrease in standing losses of 49 percent. This reduction in standing losses is due to the improved insulation resulting from the operation of the refrigerator components. As the refrigerator operates, the primary condenser and the compressor reject heat energy to the water in the HS. This warms the water and the hotter water then reduces the standing losses form the HWC because of the greater thermal resistance posed by the water.

5.2. Refrigerator performance

Refrigerator performance was not affected by the HEC configuration. The lack of effect of the HEC system on the refrigerator was because of the secondary condenser retained on the back of the refrigerator. Regardless of the effectiveness of the primary condenser in condensing the refrigerant, the refrigerant leaving the secondary condenser was at the same temperature and pressure for both the HEC configuration tests (3 and 5) and refrigerator configuration tests (2). This meant that the capillary inlet conditions were the same for both configurations and the cycle was maintained.

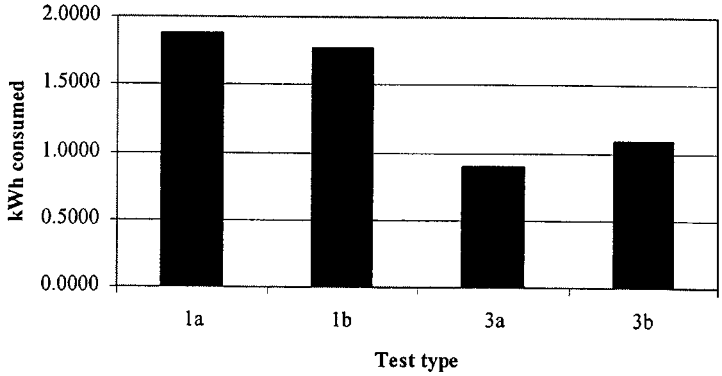

Figure 4. Electric element power consumption for standing tests ('a' and 'b' after a test type number are used to differentiate between two tests of the same test type).

5.3. Refrigerator input

The input of the refrigerator into the circuit came from the condenser and the compressor. The condenser input has been analysed using enthalpy changes, whilst the compressor input has been estimated using a resistance analogy.

5.3.1. Condenser. Figure 5 presents the total enthalpy changes of the refrigerant as it condenses in the primary (i.e. HEC) condenser and in the secondary (ie refrigerator) condenser.

The figure shows that the primary condenser is only removing about 10% of the total energy in the refrigerant for all the tests except the refrigerator input test, type 6. This meant that the average enthalpy change of the refrigerant in the primary condenser was 7·9 kJ kg^{-1}. An estimated mass flow rate of the refrigerant was about 0·0015 kg s^{-1}, which yielded an energy input just under 12 W from the primary condenser to the HS. However, for the refrigerator input test the enthalpy change in the primary condenser was almost 80 kJ kg^{-1}. This equated to an energy input of approximately 120 W. The reason for this large improvement in primary condenser performance was the lower temperatures in the empty HS which meant that the refrigerant could cool from the state of a super heated vapour to a condensing two phase mixture in the primary condenser.

In the other tests, the temperature of the HS water was too high to allow condensing of the refrigerant in the primary condenser and the refrigerant could only undergo superheat cooling. In these tests, the secondary condenser is utilised to condense the refrigerant by rejecting approximately 90% of the energy to the ambient. This has two effects. Firstly the cycle is maintained but secondly, the primary energy input of the HEC system for water heating by refrigeration energy recovery is failing to function as was originally designed and expected.

5.3.2. Compressor shell input. The heat fluxes from the compressor shell to the HS are calculated using the resistance analogy described earlier. Owing to the consistent temperatures recorded in the HS and in the compressor shell, the average temperatures for each testing period are used in the calculations, as shown in Table 2. The UA coefficients used to describe the heat transfer between the compressor shell and the HS are also given in Table 2. the compressor shell sits in nodes 1 and 2 of the HS (see Figure 3) so two heat flow rates are needed to describe the heat transfer from the compressor shell to the HS. UA_1 and the heat flow rate, $\dot{Q}_1$ are respectively the overall heat transfer coefficient and the heat flow rate between the compressor shell and node 1 of the HS, or the middle node in Figure 3. UA_2 and $\dot{Q}_2$ similarly describe heat transfer between the compressor shell and node 2, or the bottom of the HS. $\dot{Q}_{Total}$ is the summation of $\dot{Q}_1$ and $\dot{Q}_2$.

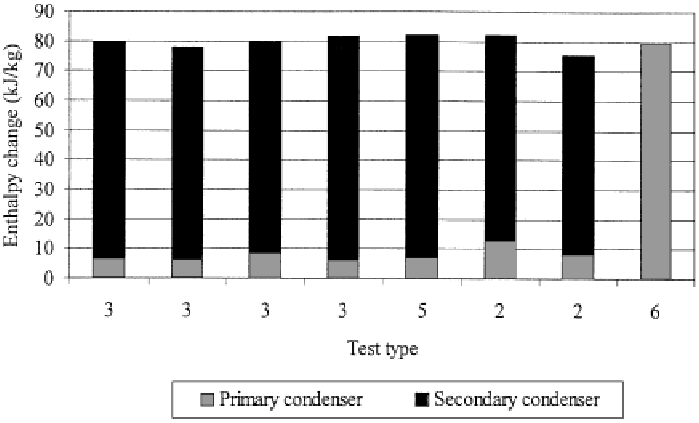

Figure 5. Enthalpy changes in primary and secondary condensers.

Table 2. Rate of heat transfer from compressor shell to heat sink

Test type	*UA* Coefficients		T_{compoil}		T_{HS}	Heat rates (W)		
	UA_1 (W/°K)	UA_2	node C	node 1	node 2	$\dot{Q}_1$	$\dot{Q}_2$	$\dot{Q}_{\text{Total}}$
3a	3·32	1·63	42·6	37·5	36·6	16·9	9·8	26·7
3b	3·32	1·63	52·9	45·5	43·6	24·6	15·2	39·7
5	3·32	1·63	50·9	35·3	30·4	51·8	33·4	85·2
6	3·32	1·63	35·9	28·2	27·7	25·6	13·4	38·9

With the poor condenser performance, the compressor shell has become the major heat source for the HS, except for energy lost from the HWC. This means that instead of the HS receiving 100 W from the condenser with additional input from the compressor, the compressor is contributing the majority of the heat energy. Specifically, the primary condenser rejects 12 W to the HS whilst the compressor averages 50 W, yielding a total of 62 W where in excess of 150 W was anticipated. This meant that the HEC concept, to utilise the normally rejected heat energy from a refrigerator to heat hot water was not being realised. The HEC draw test, type 5 shows the largest heat flow rate from the compressor to the HS. This is because during the test the water flowing through the HRC recovered some of the stored energy from the HS, which then cooled the HS water. With the reduced temperatures in the HS the temperature differential between the HS and the compressor shell increased, and this larger driving force enabled a greater heat flow rate, as can be seen in Figure 6.

5.4. Draw off tests

The draw off tests, (test types 4 and 5), produced some of the most positive results with an average $\phi = 0{\cdot}46$ for power consumption, meaning less power consumption, and a faster recovery time. The system also did not require any element input to recover after the 6·25 l draw, which suggests the heat energy transferred into the HWC during drawing was enough to maintain the HWC temperature. The test data is presented in Table 3, which gives the energy input from the element required for the system to recover. In this test, the HEC system showed good potential, with a 40 percent energy saving, when compared to the normal HWC.

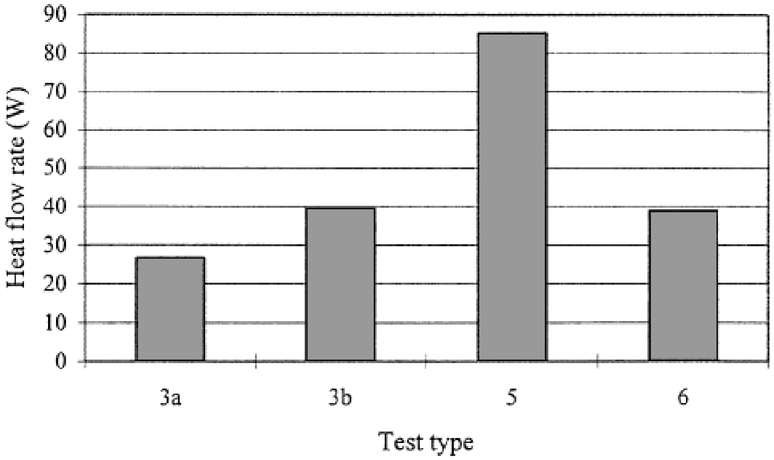

Figure 6. Heat flow rate from the compressor to the heat sink (HS).

Table 3. Summary of HEC and heater only draw-off tests

Test type	Energy input to the resistance heater (kWh)			
	6.25 l draw	12.5 l draw	25 l draw	total
4a	0·20	0·52	0·96	1·68
4b	0·21	0·50	0·95	1·66
5	0·00	0·36	0·64	1·00
ϕ	0	0·71	0·67	0·60

5.5. Heat recovery coil (HRC)

In order to estimate the energy recovered from the HRC a heat transfer analysis was performed on it. The heat transfer $\dot{Q}_{HRC}$ was calculated using Equation (9) and the energy recovered from equation (10). These results are presented in Table 4.

This test produced a positive result for the HEC concept as the HEC system outperformed the conventional HWC in all three cases, as can be seen in Figure 7. The HEC system recovered 52% more energy for the 6·25 l draw than the conventional HWC configuration. For the remaining two draws the system recovered 55 and 56% (respectively) more energy than the conventional HWC. These large amounts of recovered energy meant the system needed a reduced energy input from the conventional electric resistance heater placed in the HWC to boost the water temperature to the desired level. In summary, the HEC system was able to recover 1700 kJ more energy (Table 4). In addition, the power consumed by the electric resistance heater element, to recover the water temperature, was reduced by 40%.

5.6. Analysis of temperatures in the heat sink and hot water cylinder

Despite the positive results from the draw off tests in Sections 4·4 and 4·5 the system is not functioning as intended. This is explored by considering the temperatures measured in the heat sink tank. Figure 8 shows the temperatures at the bottom and the top of the heat sink tank and the compressor oil. Also shown is the

Table 4. Heat flow rate and energy recovery in drawoff tests

Test type	Draw type (l)	$T_{mains, in}$	$T_{HRC, out}$	$\dot{Q}_{HRC}$(kW) heat rate	$E_{recovered}$ (kJ)
4 (HWC)	6·25	14·3	34·6	6·37	509·6
	12·5	14·7	33·2	5·81	928·8
	25	15·2	31·7	5·18	1656·9
5 (HEC)	6·25	11·7	42·5	9·67	773·2
	12·5	11·5	40·2	9·01	1441·0
	25	11·6	37·3	8·06	2580·7

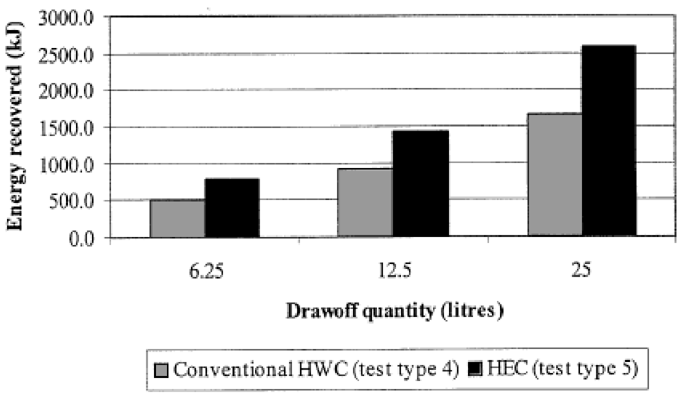

Figure 7. Energy recovered in draw off tests.

temperature difference between the bottom and the top of the heat sink (HS). This data shows that the heat energy losses from the HWC are high which heat the HS water. As a result, the elevated temperatures prevent the refrigerant from condensing in the primary condenser. The refrigeration process, however, is unaffected because the secondary condenser is utilised to maintain the cycle. This means that the majority of the refrigeration energy is not being stored in the HS for recovery, and is still being rejected to the ambient. In addition to this, the high temperatures in the HS from HWC losses mean the reduced refrigerator energy input to the HS is trapped at the base of the HS by the temperature gradients. This higher temperature water localises the inputs of the compressor and the condenser to the bottom of the HS. Therefore, the energy that is recovered by the HRC in the HS is energy that is lost from the HWC, and not energy that is supplied by the condenser and compressor of the refrigerator.

These results however do show an improved insulation effect for the HWC, which is reflected in the reduced standing losses. They also suggest energy recovery is possible but the source of the recovered energy is not the intended one. The HWC loses heat to the HS, which insulates it from the surroundings, and in addition, can be recovered by the HRC running through the heat sink.

The refrigerator standing test (type 2) further suggests the localisation effect where the HS increases in temperature by a similar amount throughout the whole tank. This means there is heat transfer from the refrigerator components throughout the HS. However, when superimposed onto the heater standing loss test, there would be no temperature differential to transfer energy from the condenser and compressor to the HRC. The temperature differential caused by losses from the HWC in fact drives heat energy towards the bottom. This effect is what prevents the unit from recovering the refrigeration energy and prevents the HEC condenser from functioning effectively.

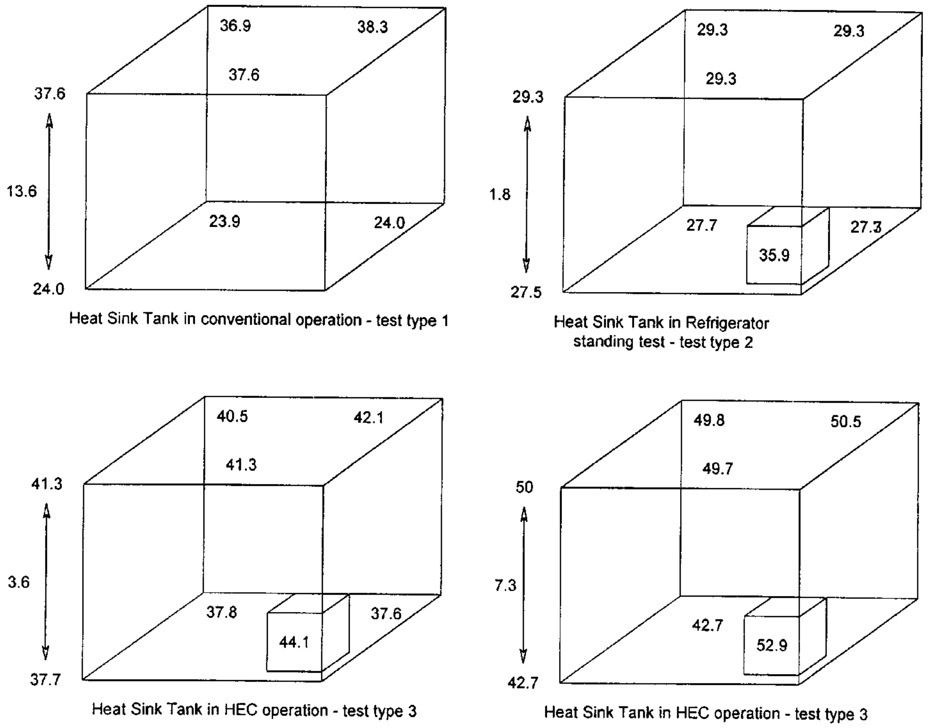

Figure 8. Temperatures (°C) within the HS during testing.

6. DISCUSSION

From the foregoing discussion, the authors believe that the HEC concept should work. A device that heats water is placed in a tank that is heated by another device. This increase in temperature means the first device loses less energy to the surroundings because of the greater thermal resistance posed by the tank. The tests have demonstrated that the system can work and these results are:

(1) The reduced standing losses from the HWC in HEC configuration, largely due to increased HS temperatures that reduce heat energy loss.
(2) The partially successful transfer of waste heat energy from refrigeration to the HS where it can be recycled, even if the majority of condenser energy is still rejected to ambient.
(3) All the draw off tests resulted in reduced power consumption to HWC recovery. In addition, for the smaller draw duration, the HWC recovered without the need for element input.

Despite these positive results, the system still does not function as originally intended. Whilst the refrigeration process does contribute energy to the HS, that energy is not available for recovery by the HRC. This is because the energy from the condenser and compressor is trapped at the base of the HS by energy lost from the HWC to the water above. The losses from the HWC create a temperature gradient that prevents the energy from the refrigerator components from transferring to the top for recovery by the HRC. This means the recovered energy during the HEC draw-off tests is energy that has been already lost by the HWC, not recycled refrigerator energy. In addition, these losses also prevent condensation in the HS because of the high temperatures. Figure 9 summarizes these effects.

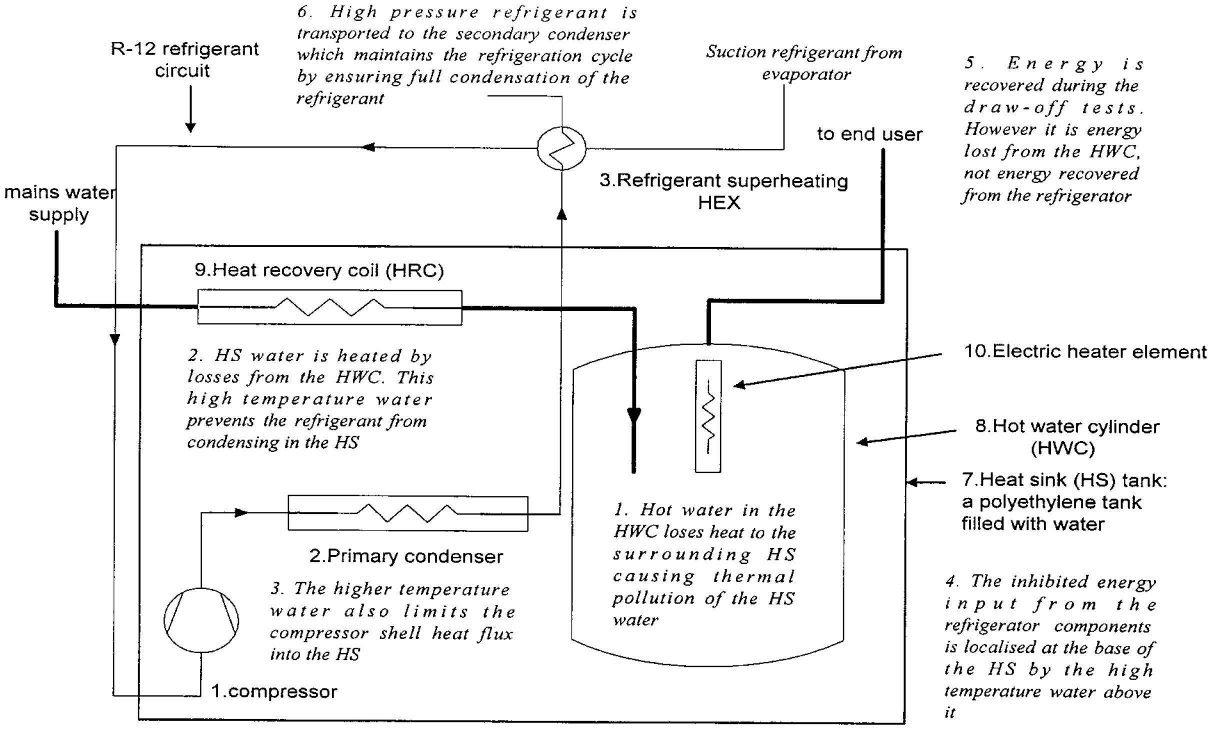

Figure 9. Effects of HWC thermal pollution on the HS and refrigerator components.

The primary cause for this situation is the insulation between the HWC and the HS. If the insulation around the HWC could be improved, along with other features of the design, then the concept might work. Better insulation will mean that less energy is lost from the HWC to the HS and this will lower temperatures and result in two things:

(1) The condenser will be able to operate as in the refrigerator only test (test 6) and start condensing in the HS, thus enabling the HS to absorb approximately 100 W when the refrigerator operates.
(2) The energy from refrigeration will be transferred to the upper regions of the HS because of the reduced temperatures. This effect was demonstrated in the refrigerator only test (test 6). This will mean that the energy recovered by the HRC will be from the intended source, not the HWC.

Other changes that would improve the performance of the system can be made to the compressor shell and the primary condenser in HEC.

- In the current design, half the compressor shell surface faces towards the surroundings, away from the HS. Placing the compressor shell in the middle of the HS, underneath the HWC, will ensure only one surface faces away from the HS.
- The primary condenser is a part of the design that does not function well. The length of the condenser should be increased to give more heat transfer area for energy rejection. It should be designed that the refrigerant is transported to the top of the HS tank after exiting the compressor. From there, the condenser should spiral down the HS to the base of the HS tank, where it exists. This will space the condenser better for heat transfer, and create a counterflow heat transfer process.

7. CONCLUSIONS AND RECOMMENDATIONS

A new design of a combined refrigerator and water heater assembly for domestic use has been presented in this paper. One benefit of the system is found to be reduced standing losses from the HWC without any major adverse effects on the refrigerator performance. The system is also found to be particularly attractive when water is drawn from the water tank. The HEC system was able to recover 1700 kJ more energy (Table 4). In addition, the power consumed by the electric resistance heater element, to recover the water temperature, was reduced by 40 percent. The compressor shell has been the main source of heat from the refrigeration unit to heat water in the HS with an average heat flow rate of about 48 W. The primary condenser rejected only 10 percent of its available energy to the HS and therefore, the system, in its current design was not able to deliver the expected energy recovery from the refrigeration waste heat. The design should be able to perform up to expectations if:

(i) The insulation between the HWC and the HS is improved to reduce thermal losses from the HWC to the HS. This will enable refrigerant condensation in the HS and prevent the localization of the refrigeration energy at the HS base.
(ii) The compressor is positioned at the bottom centre of the HS to reduce heat losses to the surroundings.
(iii) The primary condenser is enlarged and repositioned as a counterflow heat exchanger, spiralling down the HS from the top to the bottom.

Other possibilities also exist for using the concept of utilising the waste heat of refrigeration to heat water:

(i) The HS could be used as a reservoir of pre-heated water for the HWC. This would mean the mains water would enter the HS, be preheated by the refrigerator components and then flow into the HWC for boosting to final use temperatures via the element.
(ii) The HWC could be removed entirely from the HEC assembly to prevent thermal losses from the HWC to the HS.

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NOMENCLATURE

A	= area	(m^2)
COP_{HEC}	= coefficient of performance of the HEC prototype	
COP_R	= coefficient of performance of a refrigerator	
C_p	= specific heat (of water)	($kJ\,kg^{-1}$)
$E_{recovered}$	= energy recovered by the HRC during a water draw	(kJ)
h	= convective heat transfer coefficient	($W\,m^{-2}\,K^{-1}$)
k	= thermal conductivity	($W\,m^{-1}\,K^{-1}$)
$\dot{m}_{H_2O}$	= mass flow rate of water	($kg\,s^{-1}$)
$\dot{m}_{R\text{-}12}$	= mass flow rate of refrigerant R-12	($kg\,s^{-1}$)
N	= compressor frequency	($rev\,s^{-1}$)
$\dot{Q}_{comp}$	= heat flow rate from the compressor shell to the HS	(W)
Q_L	= rate of heat removed from a refrigerated space	(W)
Q_{HEC}	= rate of heat recovered by he HEC system to preheat mains water	(W)
Q_{H1}	= rate of heat rejected to the surroundings by the refrigerator condenser	(W)

Q_{H2}	= rate of heat rejected to the surroundings by the secondary condenser	(W)
$\dot{Q}_{HRC}$	= rate of heat transfer from the HS to the mains water in the HRC	(W)
$\dot{Q}_{PC}$	= rate of heat rejected from the primary condenser to the HS	(W)
$T_{discharge}$	= compressor discharge temperature	(°C)
$T_{P.C}$	= temperature of R-12 upon exit from the primary condenser	(°C)
t	= thickness	(m)
$W_{net, in}$	= net work input to the refrigeration cycle	(W)
U	= overall heat transfer coefficient	($W\,m^{-2}\,K^{-1}$)
$\dot{V}$	= volume flow rate	($m^3\,s^{-1}$)
v	= specific volume of R-12	($(m^3\,kg)^{-1}$)
η_{vol}	= volumetric efficiency	
ϕ	= power consumption ratio	

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