ENERGY EFFICIENT REFRIGERATION

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Abstract: *This article describes a household refrigerator that requires about 0.1 kWh per day to operate. The refrigerator offers excellent food-preserving performance, because temperature fluctuations in its interior are naturally minimized during everyday use. This fridge is 10 to 20 times more energy efficient than typical household fridges on the market today. It seems that the biggest obstacles in increasing the energy efficiency and food-preserving performance of household refrigerators are strange human habits and lack of understanding of Nature, not technology or cost.*

Chest fridge

Comparing the daily energy consumption of various refrigeration devices available on the market reveals that well-designed chest freezers consume less electricity per day than refrigerators of comparable volume, even though freezers maintain much larger interior-exterior temperature difference (their interiors are much cooler). While chest freezers typically have better thermal insulation and larger evaporators than fridges, there is another important reason for their efficiency.

Vertical doors in refrigeration devices are inherently inefficient. As soon as we open a vertical fridge door – the cold air escapes, simply because it is heavier than the warmer air in the room. When we open a chest freezer – the cool air stays inside, just because it's heavy. Any leak or wear in a vertical door seal (no seal is perfect) causes significant loss of refrigerator efficiency. In contrast, even if we leave the chest freezer door wide open, the heavy cool air will still remain inside.

Designing and marketing refrigeration devices with vertical doors is clearly an act against the Nature of Cold Air. Shouldn't we cooperate with Nature rather than work against it?

In 2004 I became really curious just how efficient a "chest fridge" can be. After contacting some leading fridge manufacturers and discovering they never made and tested a concept of a chest fridge, I decided to make my own test. I bought a well-designed chest freezer (Vestfrost SE255 chest freezer with 600a refrigerant) and converted it into a fridge.

Converting chest freezer into fridge

The main difference between a freezer and a fridge is the temperature maintained inside. Freezers maintain sub-zero (freezing) temperatures down to -25^{o} C, while fridges operate somewhere between $+4^{o}$ and $+10^{o}$ C.

Hence, turning a freezer into a fridge means changing the temperature control. Rather than interfering with the thermostat of the freezer, I decided to install an external thermostat to cut the power off when the temperature of my choice is reached. The block diagram in Fig 1 illustrates the idea.

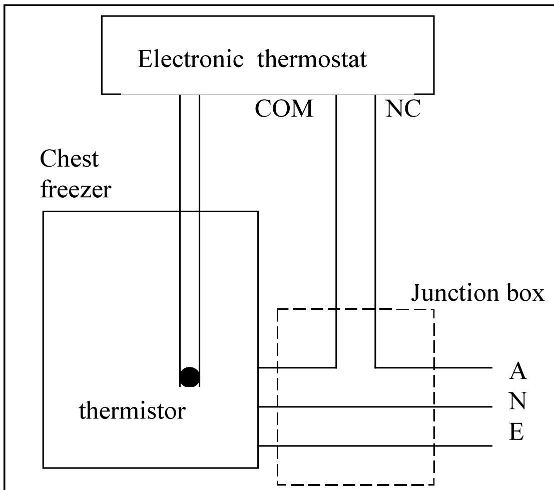


Fig. 1. Wiring diagram of the chest freezer converted into chest fridge. Active (A) connection passes via relay terminals inside the thermostat.

Connection diagram (Fig 1) is really simple. Thermostat relay cuts the power to the freezer. Thermistor (the temperature sensor) is placed inside the freezer at the end of a thin 2-wire flexible cable. I used the freezer drain hole to pass the thermistor cable inside the cooling compartment.

I have also removed the fridge interior light bulb, rated 15 Watts, because I avoid wasting energy as a matter of principle. I may consider installing a LED interior illumination if I find a reason for opening my fridge in the dark.

Thermostat design

Although, in essence, the thermostat function is very simple, design of a really good freezer-to-fridge thermostat system is not quite trivial. There are some unexpected problems and challenges that only become apparent when one aims to design a system that meets all required criteria and works really well.

Thermostat requirements

1. Reliability. Fridges need to be very reliable household devices, simply because our health depends on their reliability. Excessive temperature fluctuations due to any malfunctioning of the thermostat accelerate food spoilage and introduce the associated health risks. The thermostat should work unattended for years if not for decades.
2. Safety. The 240V power supply to the fridge should be well insulated from all low-voltage electronic components of the thermostat.
3. Zero mains (240V) power consumption during the standby period (when the fridge compressor is off). This requirement is **critical** in the situation when a modern inverter with a power-demand-sensing feature powers the fridge (in the case of a solar-powered chest fridge). Using zero-standby-power appliances allows inverter users to save up to 0.4 kWh per day just by allowing the inverter to enter the low-power-consumption standby (sleep) mode at every opportunity. Inverter-based energy savings of up to 0.4 kWh/day need to be considered in the context of the daily energy consumption of the chest fridge of 0.1 kWh. The zero-standby power requirement turned out to be the greatest challenge in the practical thermostat design.
4. Hysteresis. The number of fridge compressor starts per hour should be kept low, not only to conserve energy, but also to minimize the compressor wear.
5. The thermostat should be easy to install and should not require any modifications to any freezer, so that a new freezer warranty is not compromised in any way.
6. The thermostat should be simple and easy to construct from readily available low cost components

Zero-standby-power challenges

The general trend in modern industry is to replace electro-mechanical relays and contactors by solid-state semiconductor relays. In our case, however, this clashes with the requirement 3. Solid-state AC relays have significant capacitance when off. This means that when they are connected in series with a motor (a resistive/inductive load) they allow a small AC current to flow through the motor windings, even when everything is off. This current causes a direct continuous power loss of about 0.5 Watt (as measured with my Vestfrost freezer compressor) and the additional power loss of about 20W to keep the 24VDC-240VAC inverter active.

Solid-state power switching becomes very attractive when refrigeration compressor motor is powered by a DC power source. Since AC semiconductor switches and relays cannot meet the zero-standby-power requirement, we have to consider them unsuitable for our AC fridge application.

Hence, for a standard AC powered refrigerator, we need to settle for a properly rated relay. After experimenting with a few brands and designs, I decided to use OMRON G6RN-1A DC12 relay. In addition to its ability to handle small inductive load, and low-energy switching, it has about 7kV insulation between its 12V coil and its 240V contacts, which I consider important from the safety point of view.

Due to the zero-standby-power requirement, all electronics of our thermostat, including the temperature-sensing system, need to be powered from a battery-based power supply.

Since we also require our system to work unattended for years (or decades) we have another challenge to meet: design of a UPS (Uninterrupted Power Supply) that can work for many years unattended. The battery in this UPS needs to be charged when the fridge compressor is turned on.

The design

The schematic of the system that I currently use is depicted in Fig 2. It is a result of a compromise between the minimal possible power consumption, simplicity and the cost of components. The temperature sensing system consists of thermistor R1 (BC 2322 640 54103, 10kΩ @25ºC) interfaced with an op-amp. The LM324 quad op-amp that I selected has quite low power consumption (<0.7 mA) and can operate from single voltage power supply, which greatly simplifies the design.

U1C and U1D serve as buffers, to minimize the power consumption taken by the temperature measurement and comparison system down to negligible values. U1B is a summing amplifier. U1A is a Schmidt trigger with easy to adjust hysteresis (by changing R13), set here at approximately 0.5ºC. Capacitor C4 prevents radio signals that may appear on the long thermistor R1 cable from interfering with functioning of the system.

The switch SW1 addresses the issue of powering the system down (the center-off position) and allows the thermostat to operate in two modes: powered by mains 240V ("SW1 up", in which case the battery can be removed) and from the battery ("SW1 down", the zero-standby-power mode). The "SW1 up" mode also addresses the issue of the initial charging of the battery.

Note the use of the micro-power LM2936 as a 5V regulator. Typically used LM7805 would by itself consume 5 times more power than the entire circuit and would prevent the entire system to become classified as micro-power. Using LM7805 would make battery discharge cycles 5 times deeper and hence requiring 5 times larger capacity battery for sustained operation, not to mention a larger transformer to keep the battery charged.

In "SW1 down" mode, the battery is charged when the freezer relay and the compressor are on, which, for my Vestfrost fridge, is between 1 and 2 minutes per hour. The rest of the time, the thermistor circuitry is powered up by the battery, and it does not draw any current from the 240V mains supply.

During the system operation, the nominal 8.4V NiMh battery voltage varies between 9.2V and 9.4V, so that in practical terms the battery remains fully charged and hence can operate for many years.

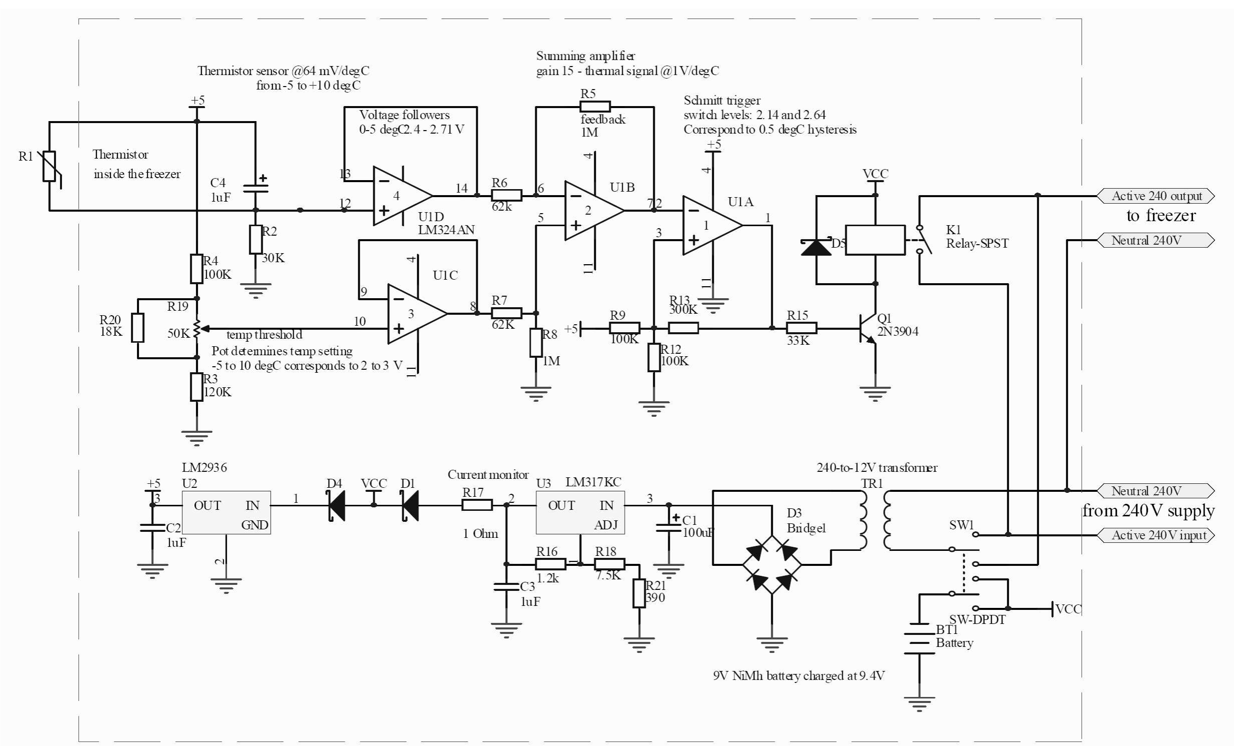


Fig 2. Schematic of the zero-standby-power freezer-to-fridge thermostat. Earth connection (not shown) must be carried from the AC power supply cable to the freezer supply cable. Suitably rated MOV (metal oxide varistor) installed between 240V output and the neutral terminals can help to protect the lifespan of the relay

When choosing the transformer, we need to be aware of its magnetizing current specifications and choose the one with the minimum magnetizing current, if possible. In my design I used an inexpensive 2VA transformer with built-in thermal fuse and the magnetizing current <20mA. Since the battery charger section (transformer TR1 and LM317 regulator) only work 1-2 minutes per hour, their optimization was not attempted.

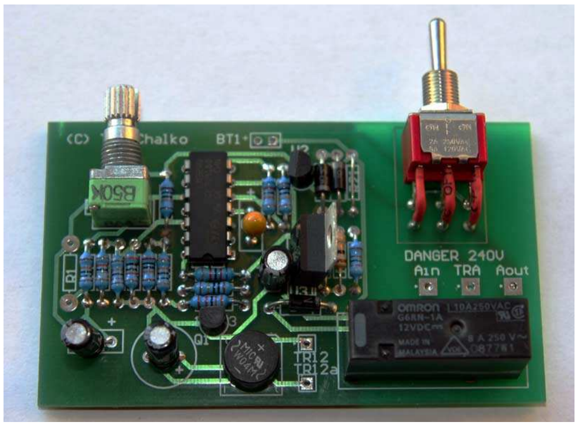


Fig 3. The printed circuit board of the thermostat is double-sided and has insulating solder masks to maximize the circuit safety and reliability.


Fig 4. Inside the assembled thermostat. The thermostat enclosure is waterproof. Right: transformer. Left: the 9V NiMh battery.

Installation

The thermostat system described above is designed to be installed along a power cable that delivers AC power to the freezer. No freezer modification is needed. The well-sealed thermistor, soldered at the end of a thin cable of sufficient length, needs to be inserted into the freezer interior. This is best achieved using a freezer-draining hole.

The location of the temperature sensor is important. If the thermistor is left near the bottom of the chest fridge interior – the thermostat will control the minimum fridge temperature. If the thermistor is located near the top of the cooling compartment – the thermostat will control the maximum temperature there. The most practical position for the thermistor is somewhere in the middle.

In my fridge the thermistor is supported at the desired location above the fridge interior floor using a piece of a polyethylene tube held in one of the corners. The temperature sensor supported this way measures the temperature of the air inside the fridge interior, rather than the temperature of the metal wall.

Temperature measurement

I have deliberately omitted temperature measuring and display from my thermostat design in order to keep the design as simple as possible. What helped me in this decision was an abundance of the temperature measuring devices available on the market. Personally I use a "dual thermometer" with its "remote" temperature sensor well sealed with silicone. It measures and displays 2 temperatures: one inside the fridge and one in the room outside it.

The weak point

The thermostat design above has one weak point. When the mains power (220-240V) is not available and the fridge interior temperature rises, the 60mAh battery will power the relay coil up for a 3-4 hours and then will go flat. Using a larger capacity battery can extend this time.

I have doubts if this issue requires attention, because if the power goes down for many hours, the content of any fridge, no matter how advanced, will need a very careful inspection and manual intervention.

When the power is restored, my system will require switching to the "SW1 up" mode for a day or so, so that the battery becomes fully charged.

Performance

Results of my freezer-to-fridge conversion experiment exceeded all my expectations. My chest fridge outperforms any conventional vertical door fridge in every respect, including energy efficiency, food preserving performance and the convenience of everyday use.

I have never seen a fridge that was **so** quiet. It only works ~90 seconds or so every hour. At all other times it is perfectly quiet and consumes no energy whatsoever. My wind/solar system batteries and the power-demand-sensing inverter simply love it.

One of the most impressive features of a chest fridge is its excellent food-preserving performance. After all, the main function of a refrigerator is helping us to preserve food.

Improvement in food-preserving performance is attributed to minimal temperature fluctuations in a chest fridge during everyday use. In most parts of my chest fridge interior the temperature fluctuations are limited to approximately ±1.5ºC.

In ~5 years of using my chest fridge to store vegetarian food I cannot remember throwing away any food that has spoiled in it.

The chest-style refrigerator is surprisingly practical and convenient to use. The most frequently used items are placed in top baskets and are very visible and very easily accessible. Baskets slide on top edges of fridge walls so that quick access to deeper sections of the fridge interior is possible without removing any basket.

At the bottom of the fridge interior I store food in suitably sized large cardboard boxes resting on rubber feet. The function of rubber feet is to prevent cardboard boxes from absorbing condensed water that collects at the fridge floor.

When cardboard boxes show signs of deterioration – I replace them. If I could find plastic boxes that would fit nicely at the bottom in some sort of array – I would use them.

Condensation

Condensation is a natural phenomenon that occurs in the chest fridge interior. The air on Earth always contains some moisture. When the air is cooled down – the condensation occurs.

In a chest fridge the moisture condenses on internal fridge walls and over time the condensed water collects at the bottom of the interior.

The condensed water is in essence distilled water that “rinses” the internal chest fridge walls. The amount of condensation depends how much moisture is in the ambient air and how often and how vigorously we open and close the fridge lid.

In practical household use I found that the condensed water collected at the bottom of the chest fridge needs to be sponged out every 2-to-3 months to maintain hygiene and functionality.

Global implications

Since I constructed my first prototype back in 2004 I had visitors from some 15 countries visiting me at Mt Best, Australia (http://mtbest.net) for various reasons.

Everyone has been very impressed with the ease of use and the exceptional food-preserving performance of my chest fridge.

Today (2009) a few hundred copies of my thermostat and thousands of thermostats of alternative designs are used to convert chest freezers into chest fridges on all continents.

People around the world have converted a great variety of chest freezers makes and models into chest fridges and experienced their surprising performance.

It becomes obvious that an energy efficient fridge does not cost any more money than a mediocre one. It actually costs less, especially to operate. If I had to purchase the electricity to operate my chest fridge I would only need to pay for about 37kWh per year. At 10 cents per 1kWh my cost would be about $3.70 per year.

So - why mediocre household refrigerators are being made? Why people continue to buy and use energy wasting refrigerators that cannot even keep their food fresh?

Nearly every household on Earth has a vertical-door fridge that wastes not only food, but also about 1 kWh of energy each day (~365 kWh a year). Some vertical-door fridges waste as much as 3kWh each day.

In a country of a few million households, replacing vertical door refrigerators with chest-fridges can save enough energy to allow closing down at least one large power station. Alternatively, construction of a new power station to meet the increasing energy demand could be avoided or delayed.

Ultra-low energy consumption of well-designed chest-fridges that feature zero-standby-power consumption makes them well suited to be solar-powered.

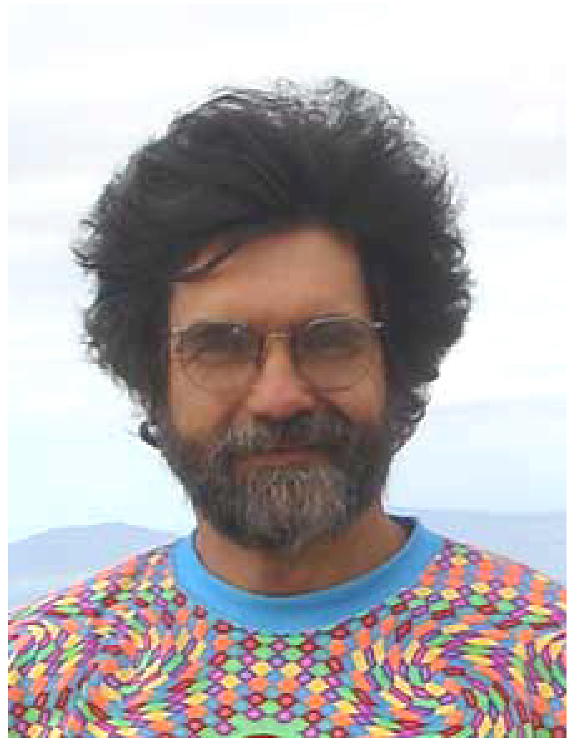
Ultra-low energy consumption combined with excellent food-preserving performance provide compelling incentives for every household on Earth to co-generate at least some part of the consumed energy using renewable power sources such as Sun and/or wind.

Transition to renewable and sustainable energy sources only makes sense when we succeed to minimize our energy waste.

People and economies that waste energy will not be able to maintain their energy-wasting lifestyle when transition to sustainable energy sources becomes necessary.

References

1. T. Chalko, A fridge that takes only 0.1 kWh a day? , *Renew* (Australia) issue 90 (2005)
2. T Chalko, My thermostat design, *Renew*, (Australia) issue 93, 2005
3. T.Chalko, Sustainable energy household, http://mtbest.net



Dr Tom Chalko holds MEngSc in Mechanical Engineering since 1975 and PhD in physics (Laser Holography) since 1979. He is an author of 3 books and numerous research articles. Prior to his retirement in 2001 he was an academic at the University of Melbourne in Australia for nearly 20 years. Since 2001 Dr Chalko focuses on setting an example of energy-efficient lifestyle, relying ~100% on renewable/sustainable energy sources and living with the minimal possible footprint on the environment. His research interests span from geophysics and astrophysics to physics of Consciousness and the Purpose of Existence. Please see the reference [3] for more details.