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Modified A^{++}- standard refrigerator with 30% reduction of energy consumption

Higher efficency by compressor modification

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Abstract

Significant global impact

In Europe 14% - 20% of the electrical energy in homes is consumed by various food cooling units. A small reduction in their energy consumption would have a significant impact on the global environment. The 6 Million food cooling units in Switzerland consume about 2500 GWh/a. As a comparison: Beznau-1, a small nuclear power plant in northern Switzerland, produces 3000 GWh/a. It is fair to say that one Swiss nuclear power plant is needed just for cooling food!

27% less electricity consumption

In this work we have shown, that up to 27% electrical energy can be saved by simple modification of a class A^{++} refrigerator. The modified refrigerator was tested directly against the serial product.

Today: fixed rotation speed

Today's refrigerators run with a compressor at a fixed rotation speed, which is turned on and off by a thermostat. At room temperature and with closed doors the refrigerator runs about one forth of the time. This mode of operation is inefficient because of the frequent start-up of the compressor, high internal losses due to the high flow rates and the large thermal gradient between the cooled volume and the cooling circuit.

Compressor with variable revolution speed

The modified refrigerator was fitted with compressor with variable revolution speed. This compressor could be run at much lower speeds so that it ran up to 90% of the time. It was shown that less electricity was consumed the more the compressor ran. The compressor was controlled by a computer which at the same time collected various temperature data.

„close to series“ refrigerator

For the next step, the development of a marketable product, a „close to series“ refrigerator shall be built, which runs without external control by a computer. The cost effectiveness is very important. The end customer is not willing to pay much more for a more energy efficient refrigerator because the financial saving over the lifetime of the appliance (about 15 years) is only ~CHF 100.

Refrigerator manufacturer as a partner

It is essential to have a refrigerator manufacturer as a partner for this next step in order to make sure that we are developing in the right direction and that the necessary technical information on the refrigerators is guaranteed. A key market player would be of great interest because he would be able to put more pressure on the compressor manufacturers and the introduction of this technology in the market would have a larger impact.

1. Introduction

14% - 20% of the electricity consumed in homes is used by refrigerators and freezers. In Switzerland over 6 million appliances used for cooling foods consume 2'500 GWh electricity per year [1].

Very high energy consumption

If old or broken cooling units are replaced by class A^{++} units a lot of energy can be saved because these units only use half the energy of class A units. The step from A to A^{++} Units can save 1'250 GWh/a. Our aim of cutting the energy consumption of A^{++} units in half can save another 600 GWh/a.

Significant economization possible

In the past years most of the development on refrigerators was devoted to improvement of the isolation. The following factors limit optimiziation:

Factors that limit optimization

- The ratio of storage volume to total volume must be within sensible boundaries.
- Easy access for every day use
- It must be possible to place warm foods inside
- Cooling circuit
- Low production costs

If a modern refrigerator is closely analysed it is obvious that the main optimization potential is in the compressor [2].

Compressor

There are very few compressor suppliers worldwide (for instance Danfoss, Embraco) but many more refrigerator manufacturers, which purchase their compressors from the same place. For the refrigerator manufacturer this means that they see very little possibility of differentiation in the compressor. Thus, this is not a field of innovation. At the same time the compressor manufacturers are confronted with lots of cost pressure by the refrigerator manufacturers. So their focus is the reduction of manufacturing costs and not technical innovation.

Few compressor manufacturers

The Refrigerator manufacturers need energy efficient units to satisfy regulations and the market. However, the customers are not willing to pay much more for this innovation because the difference between a class A and a class A^{++} unit is not very visible.

Manufacturers under cost pressure

1.1. Aim

Demonstration Refrigerator

This project shall help to cut he Gordian knot described above. An A^{++} Refrigerator has been modified to show how much economization potential is in the compressor system.

1.2. Approach

Today: fixed rotation speed

Today's refrigerators run with a compressor at a fixed rotation speed. The compressor is turned on and off by a thermostat. At room temperature and with closed doors the refrigerator runs about one forth of the time. This mode of operation is inefficient because of the frequent start-up of the compressor and the large thermal gradient between the cooled volume and the cooling circuit.

Variable rotation speed

It is known out of information from literature [2] as well as past awtec projects that a compressor with variable rotation speed which runs most of the time can save more than 30% electricity compared to a standard compressor.

Less internal losses

In addition to having less start up cycles, the compressor with variable rotation speed runs at much lower speed so that the internal losses in the cooling circuit are significantly reduced. The thermal gradient between the cooling circuit and the cooled volume is also much smaller because the compressor is running most of the time.

Suitable compressors on the market

Suitable compressors with variable rotation speed were identified on the market. Thus, the development of a new compressor was not needed.

2. Compressor manufacturers

The following European compressor manufacturers were considered as potential partners:

Danfoss

Danfoss, does not offer a compressor with variable rotation speed but would be willing to cooperate in the development of such a compressor.

Embraco

Embraco, a large manufacturer producing also outside of Europe was quite cooperative. Embraco offers a range with variable rotation speed (VCC3). These compressors have already been installed in to some high priced “Food Center Refrigerators”.

ACC

ACC also offers compressors with variable rotation speed which seem to be very efficient on paper; however they did not react to multiple inquiries from awtec.

Partner

We decided to collaborate with Embraco on this project. We hoped that this would make it easy to exchange a conventional compressor with a compressor with variable rotation speed.

Collaboration difficult

Unfortunately the collaboration ended up being quite complicated because of the geographical distances as well as language and cultural barriers (development in Italy, manufacturing and stock in Brazil).

Limited information flow

The flow of information to us was very limited: Important technical information which would have significantly simplified our project was not passed on. We were also not able to get any information on production costs of the compressors.

3. Experimental

3.1. The Electrolux Refrigerator

An Electrolux EK 244 11 refrigerator was chosen fort his study. This is one of the most common class A^{++} refrigerators in Switzerland.

Electrolux

Fig. 1 Electrolux EK 244 11

The refrigerator has a total volume of 241 l (215 l for cooled products, 26 l for frozen goods). The norm consumption is 173 kW per year.

173 kW per year

The Electrolux-Unit is built by Arbonia Forster and runs on an EMX32CLC Embraco compressor.

Arbonia Forster

3.2. Compressors

3.2.1. Standard Compressor Embraco EMX32CLC

Induction motor

The standard compressor has a one phase induction motor.

A - APPLICATION / LIMIT WORKING CONDITIONS			
1 Type	Hermetic reciprocating compressor		
2 Refrigerant	R-600a		
3 Nominal voltage and frequency	220-240 / 50	[V/Hz]	
4 Application type	Low Back Pressure		
4.1 Evaporating temperature range	-35°C to -10°C	(-31°F to 14°F)	
5 Motor type	RSCR		
6 Starting torque	LST - Low Starting Torque		
7 Expantion device	Capillary tube		
8 Compressor cooling		Operating voltage range	
		50 Hz	60 Hz
8.1 LBP (32°C Ambient temperature)	Static	198 to 254 V	-
8.2 LBP (43°C Ambient temperature)	Static	198 to 254 V	-
8.3 HBP (32°C Ambient temperature)	-	-	-
8.4 HBP (43°C Ambient temperature)	-	-	-
9 Maximum condensing pressures/temperature			
9.1 Operating (gauge)	7.7	[kgf/cm^2] (109 psig)	/ °C - °F
9.2 Peak (gauge)	9.8	[kgf/cm^2] (139 psig)	/ °C - °F
10 Maximum winding temperature	130	[°C]	
B - MECHANICAL DATA			
1 Commercial designation		[hp]	
2 Displacement	5.96	[cm^3] (0.364 cu.in)	
2.1 Bore	22.500		
2.2 Stroke	7.500		
3 Lubricant charge	180	[ml] (6.09 fl.oz.)	
3.1 Lubricants approved			
3.2 Lubricants type/viscosity	ALQUILB / ISO5		
4 Weight(with oil charge)	7.8	[kg] (17.20 lb.)	
5 Nitrogen charge	-	[kgf/cm^2]	
C - ELETRICAL DATA			
1 Nominal Voltage/Frequency/Number of Phases	220-240 V 50 Hz 1 ~ (Single phase)		
2 Starting device type	TSD		
2.1 Starting device			
3 Start capacitor	-	[µF(VAC minimum)]	
4 Run capacitor	2.5(440)	[µF(VAC minimum)]	
5 Motor protection (external)	AE23AHNX		
6 Start winding resistance	34.75	[Ω at 25°C (77°F)] +/- 8%	
7 Run winding resistance	37.70	[Ω at 25°C (77°F)] +/- 8%	
8 LRA - Locked rotor amperage (50 Hz)	2.60	[A] - Measured according to UL 984	

Fig. 2 Extract from data sheet of the refrigerator's standard compressor.

Already energy otpimized

The EMX-line of compressors from Embraco is already energy optimized with higher motor efficiency and with spezial start up electronics. The EMX compressors save about 9%[1] compared to the cheaper EMY line.

[1] Email from J. Wiest, Embraco, 11.11.2009

3.2.2. Compressor with variable rotation speed: Embraco VCC3 VEM X5C

3-Phase-EC-Motor

An Embraco VCC3 VEM X5C compressor with a 3-Phase EC Motor was used for the modified refrigerator. The revolution speed can be varied from 1200-4500 RPM.

A - APPLICATION / LIMIT WORKING CONDITIONS

1 Type	Hermetic reciprocating compressor		
2 Refrigerant	R-600a		
3 Nominal voltage and frequency	230 / 40-150	[V / Hz]	
4 Application type	Low Back Pressure		
4.1 Evaporating temperature range	-35°C to -10°C	(-31°F to 14°F)	
5 Motor type	BPM		
6 Starting torque	LST - Low Starting Torque		
7 Expantion device	Capillary tube		
8 Compressor cooling		Operating voltage range	
		50 Hz	60 Hz
8.1 LBP (32ºC Ambient temperature)	Static	187 to 255 V	187 to 255 V
8.2 LBP (43ºC Ambient temperature)	Static	187 to 255 V	187 to 255 V
8.3 HBP (32ºC Ambient temperature)	-	-	-
8.4 HBP (43ºC Ambient temperature)	-	-	-
9 Maximum condensing pressures/temperature			
9.1 Operating (gauge)	7.7	[kgf/cm²] (109 psig)	/ ºC - ºF
9.2 Peak (gauge)	9.8	[kgf/cm²] (139 psig)	/ ºC - ºF
10 Maximum winding temperature	130	[°C]	

B - MECHANICAL DATA

1 Commercial designation	1/5	[hp]
2 Displacement	5.19	[cm³] (0.317 cu.in)
2.1 Bore	21.000	
2.2 Stroke	7.500	
3 Lubricant charge	220	[ml] (7.44 fl.oz.)
3.1 Lubricants approved		
3.2 Lubricants type/viscosity	ALQUILB / ISO5	
4 Weight(with oil charge)	7.59	[kg] (16.73 lb.)
5 Nitrogen charge	-	[kgf/cm²]

C - ELETRICAL DATA

1 Nominal Voltage/Frequency/Number of Phases	230 V 40-150 Hz 3 ~ (Three phase)	
2 Starting device type	Inverter	
2.1 Starting device	VCC32456XXXX	
3 Start capacitor	-	[μF(VAC minimum)]
4 Run capacitor	-	[μF(VAC minimum)]
5 Motor protection (external)	VCC32456XXXXX	
6 Start winding resistance	16.07	[Ω at 25ºC (77ºF)] +/- 8%
7 Run winding resistance	16.07	[Ω at 25ºC (77ºF)] +/- 8%
8 LRA - Locked rotor amperage (40/150 Hz)	2.10/2.10	[A] - Measured according to UL 984

Fig. 3 Extract from data sheet of the compressor with variable rotation speed used in this work.

Inverter

Fig. 4 shows the modified compressor with its inverter. A frequency generator was necessary to give a signal to the inverter (40 Hz – 150 Hz). Different compressors of the exact same type were used for experiments. They showed slightly different performance and needed different levels of fluid in the cooling circuit.

Fig. 4 Compressor with variable rotation speed Embraco VCC3 VEM X5C with inverter

3.2.3. Comparison of the Compressors

VCC compressor slightly smaller

The VCC3 VEM X5C-Kompressor is the smallest compressor with variable roatation speed which is available from Embraco. The displacement is about 15% smaller than the standard compressor. Even so the VCC compressor has higher maximal power because it can be run a higher revolution speed.

	Standard compressor	Compressor with variable rotation speed
Model	EMX32CLC	VCC3VEMX5C
Dispalcement	3.0 cm^3	2.6 cm^3
Maximal cooling power	73 W	100 W
COP (at 3000 RPM)	1.35	1.40

Table 1 comparison of the two compressors

Efficiency

The standard compressor reaches efficiency (COP) of 1.35 under standard conditions[2], the efficiency of the compressor with variable rotation speed lies between 1.21 and 1.4 depending on the rotation speed.

[2] CECOMAV: Evaporating temperature -25°C, Condensing temperature 55°C

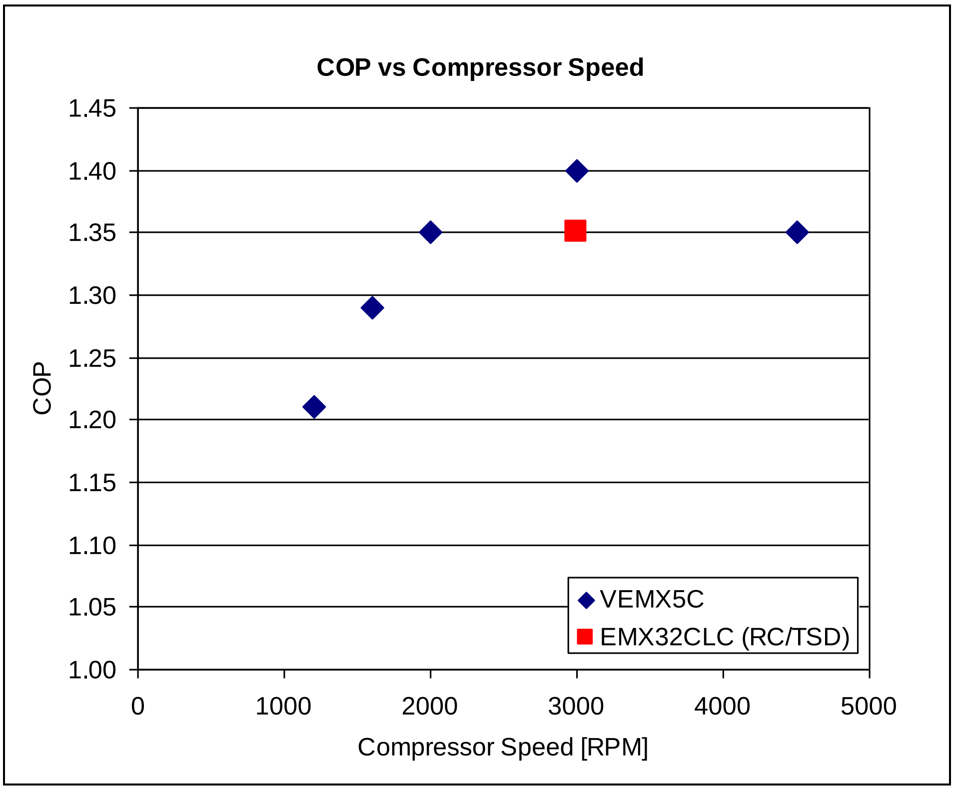

Fig. 5 COP of Standard compressor (red) and the compressor with variable rotation speed (blue) at different speeds

Lower efficiency at low speeds

Fig. 5 shows that the compressor with variable rotational speed is very efficient at high rotational speed but not nearly as efficient at the lower speeds which still led to the largest savings in electricity.

3.2.4. Installation and filling of the variable compressor

Filling system

The variable compressor was installed in the modified refrigerator. In order to experiment with different levels of cooling fluid a filling system was also integrated. Filling was possible with an accuracy of ±1g.

Fig. 6: Variable compressor with filling system

3.3. Temperature control and Data acquistion

Temperature data and electrical consumption data was collected throughout the tests (Fig. 7) from the original unmodified refrigerator in parallel with the modified refrigerator.

Fig. 7: Measurement and control system

Data collection

Thermal elements measured the following temperatures in both refrigerators:

- Air temperature cooling compartment
- Wall temperature of cooling compartment
- Air temperature of freezing compartment
- Wall temperature of freezing compartment
- Compressor feed line
- Compressor backlash
- End of condenser

In addition, the follwing temperatures were measured:

- Room temperature
- Reference (ice water 0°C)

At the same time the electrical energy consumption of the two refrigerators was measured.

Refrigerator was tested empty

It was our aim to compare the modified refrigerator with the original. In order to speed up the measurements all tests were conduced with empty refrigerators. Thus, the tests do not comply with ISO 15502. The empty refrigerator has a lower heat capacity and reacts much faster to changes than a loaded refrigerator. This has no influence on the total energy consumption in our test modus.

Direct compari-son

The two refrigerators were built into a cabinet to simulate the installation in a typical Swiss kitchen (see Fig. 8). All tests were run in direct comparison. This way we did not have to control the room temperature.

Fig. 8 Original refrigerator (left) and modified refrigerator (right) built into the same cabinet with data acquisition equipment on top

3.3.1. Software

LabView-Software

The control and data acquisition software is based on NI LabView and runs on a Windows laptop which is connected to the data acquisition unit by USB, which reads out one thermal element every 2 seconds. This results in one data point every 32 seconds for each thermal element.

Temperature control

The temperature can be controlled in different modes:

– Fixed temperature with a hysteresis and fixed rotation speed of compressor.

– Follower control, were the modified unit follows the temperature of the original unit by turning the compressor on and off at a fixed rotation speed

– Manual control

Screen shots

The data and control parameters are displayed in Lab View in order to get a fast overview (see screen shots Fig. 9 and Fig.10).

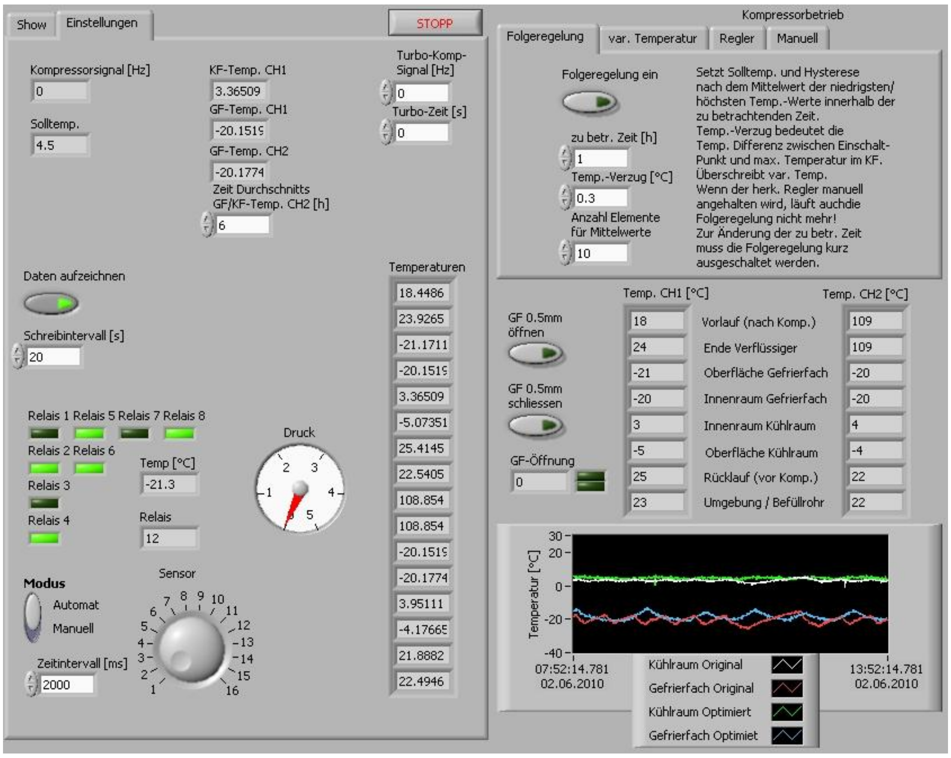

Fig. 9 *Left: Temperature data (averaged out on top), Right: Compressor control with follower control (the cooling compartment temperature of the modified refrigerator follow the cooling compartment of the original refrigerator)*

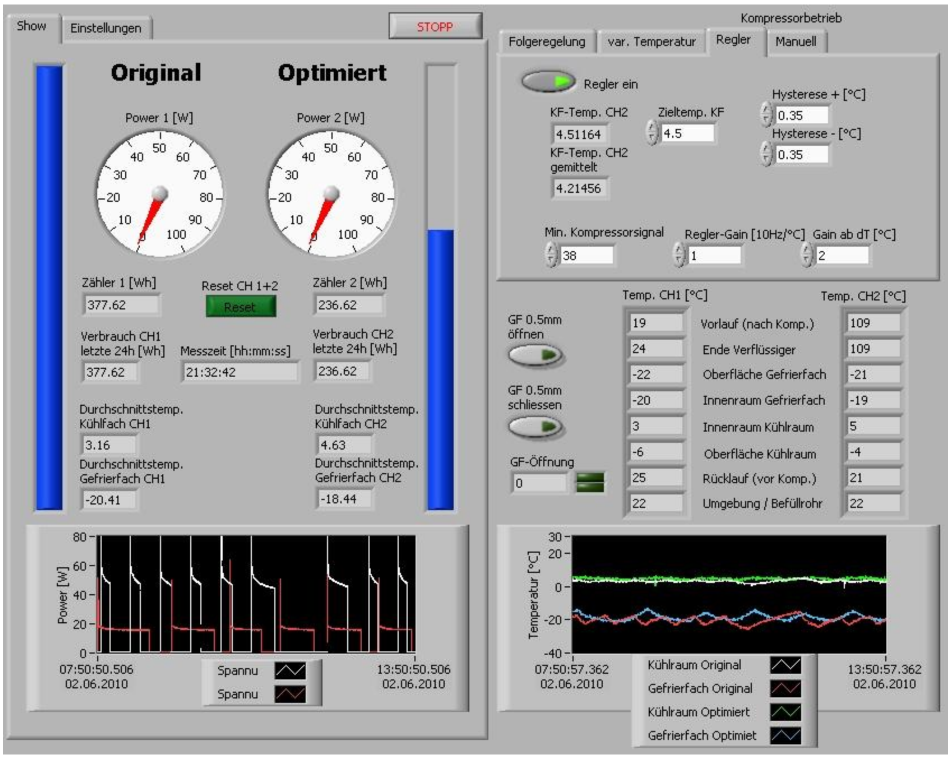

Fig.10 *Left: Energy consumption overview for both refrigerators, Right: compressor control of modified refrigerator*

4. Results

4.1. Measurement procedure

Stabilisation

A measurement was started after the refrigerator had stabilized with the new set of parameters. After a change in compressor rotation speed stabilization took a couple of hours. After a change in cooling liquid stabilisation took about one day.

Core data

Fig. 11 gives an overview of the core data during a measurement.

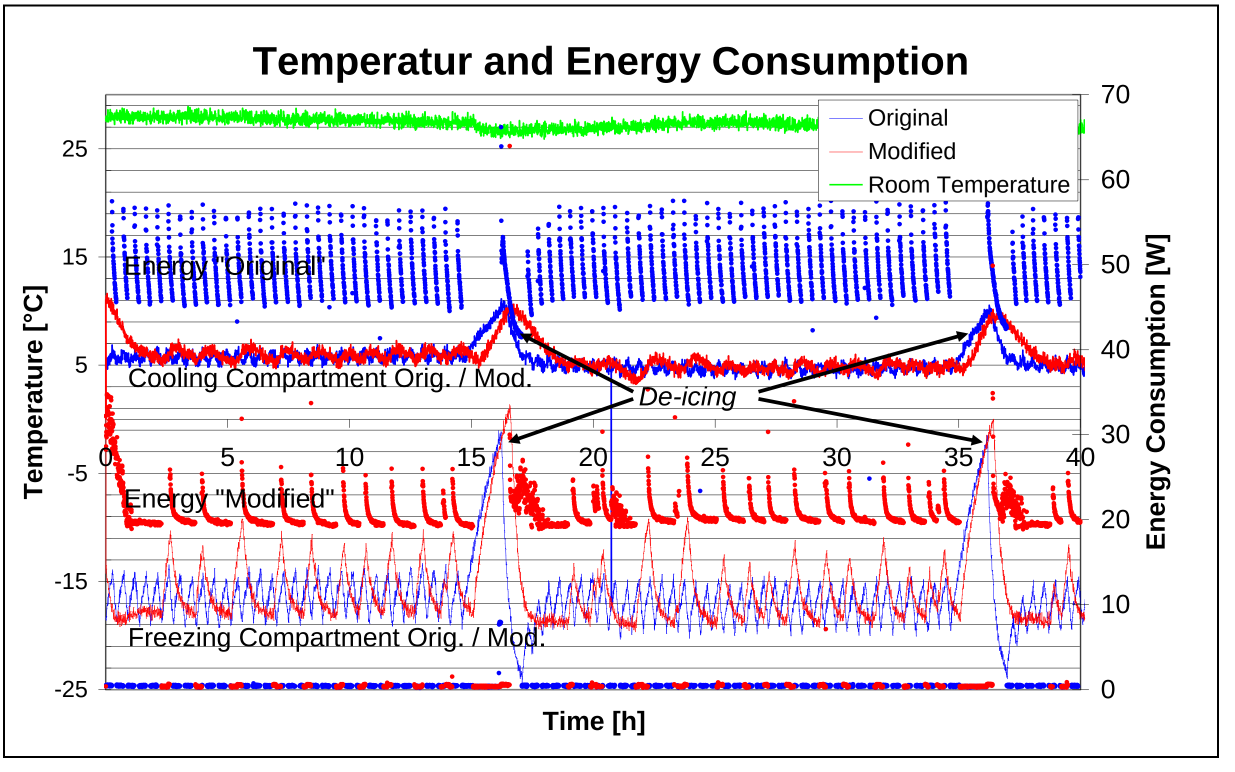

Fig. 11: Data acquisition with modified refrigerator running at 1600 RPM with 30 g of cooling fluid.

Explanation of tests

The original refrigerator was set at 5°C and its compressor always runs at 3000 RPM. The modified refrigerator was set to run at constant compressor speed (1600 U/min) and match the cooling compartment temperature of the original refrigerator. In Fig. 11 it can be seen that this leads to very different running cycles for the two units. The modified refrigerator runs about 75% of the time at low power whereas the original refrigerator only runs about 25% of the time at much higher power.

4.1.1. Temperature-corrected energy consumption

Influence of temperature deveation

In practice, it was very difficult to exactly reproduce the temperatures of the cooling compartment and the freezing compartment of the original refrigerator. Thus, the energy consumption was corrected by the temperature difference between the two refrigerators. Fig. 12 shows the influence of temperature difference of the modified refrigerator running with 42 g of cooling liquid at 2400 RPM. The temperature difference is the Sum of the temperature deviation in the cooling and freezing compartments. The linear approach leads to the conclusion that a deviation of +1°C (compared to the original refrigerator) leads to about 5% less energy consumption.

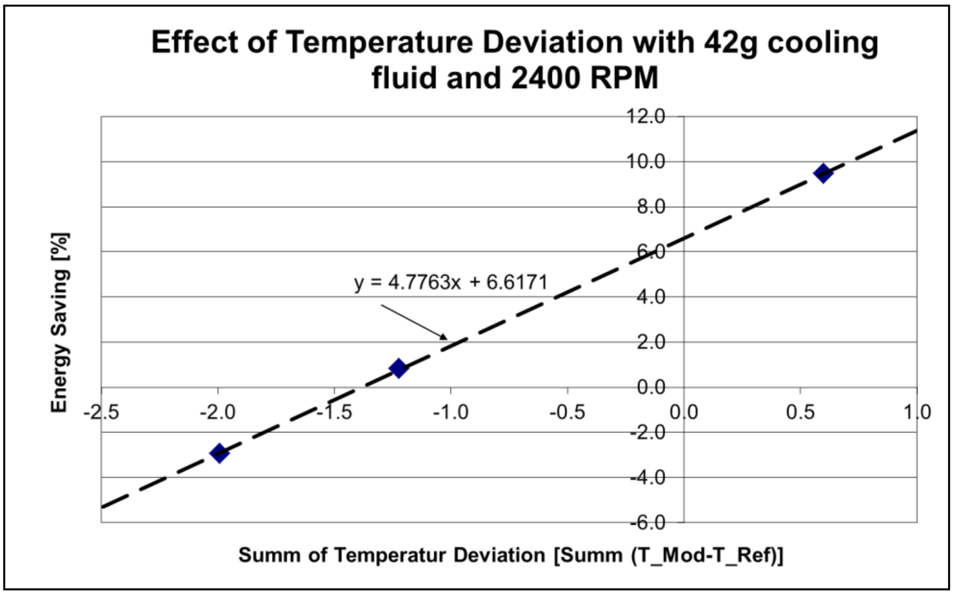

Fig. 12 Influence of the temperature deviation on the energy consumption

Corrected energy consumption

The corrected energy consumption was calculated as follows:

$$Consumption_{corrected} = Consumption_{measured} - 4.77 \cdot (\Delta T_{cooling} + \Delta T_{freezing})$$

4.1.2. Influence of the cooling fluid quantity

Variation of cooling fluid

Tests were conducted at 1600 RPM to evaluate the optimal cooling liquid quantity for each compressor we used. Fig. 13 shows the effect of cooling fluid quantity on the consumed energy.

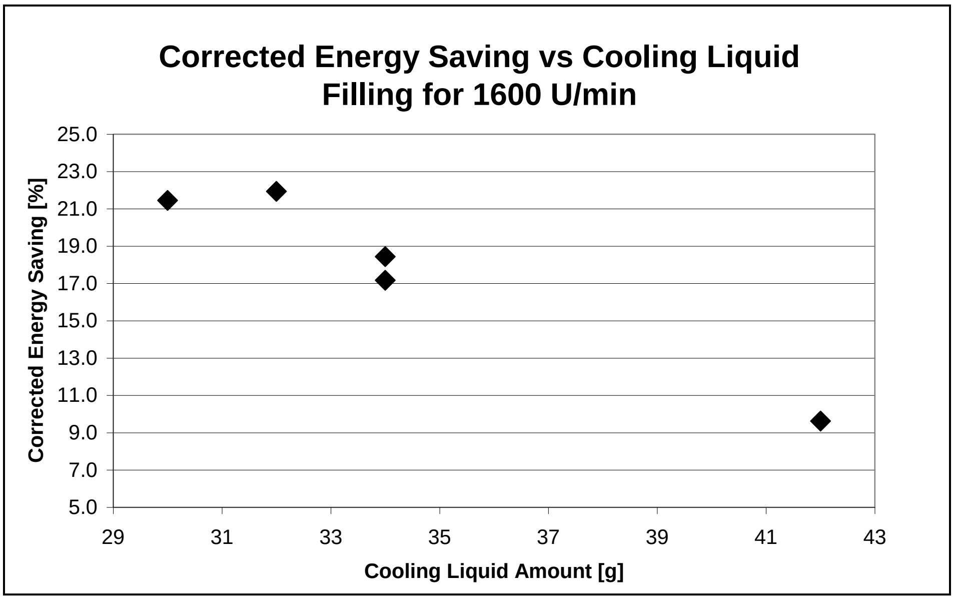

Fig. 13 Corrected energy consumption in dependence of the cooling liquid amount (for compressor 1)

Optimal filling amount 30-36 g depending on compressor

It can be seen that with this compressor the highest saving in energy is achieved at low filling amounts of 30-32 g. Other compressors of the same model needed a bit more cooling liquid (34-36 g) for optimal performance. We do not know where this deviation between the compressors came from.

4.1.3. Influence of compressor rotation speed

Lower compressor speed

Fig. 14 shows the influence of compressor speed on the energy consumption of the modified refrigerator run with 34 g cooling fluid. It can be seen that lower compressor speed leads to a significant energy saving.

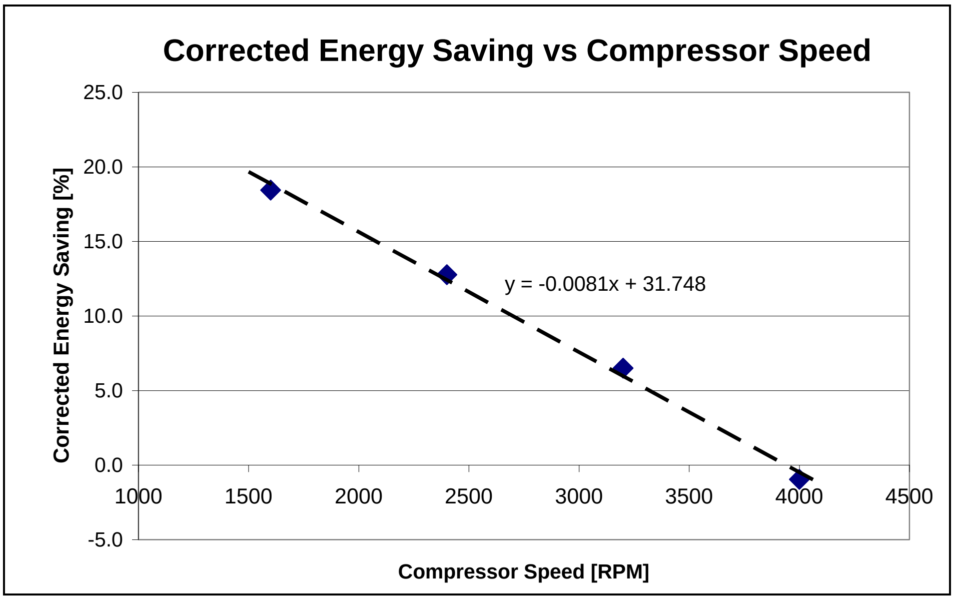

Fig. 14: Corrected energy consumption of the modified refrigerator run at different compressor speeds compared to the original refrigerator.

More ON-time

Running the compressor at 1600 RPM leads to energy saving of almost 20% compared to running the compressor at 4000 RPM. Of corse the compressor running at lower speeds is "ON" more. Fig. 15 shows the energy saving compared to the original refrigerator in dependence of the relative ON-time for 34 g cooling fluid. A relative ON-time of 2 means, that the modified refrigerator was running twice as much as the original.

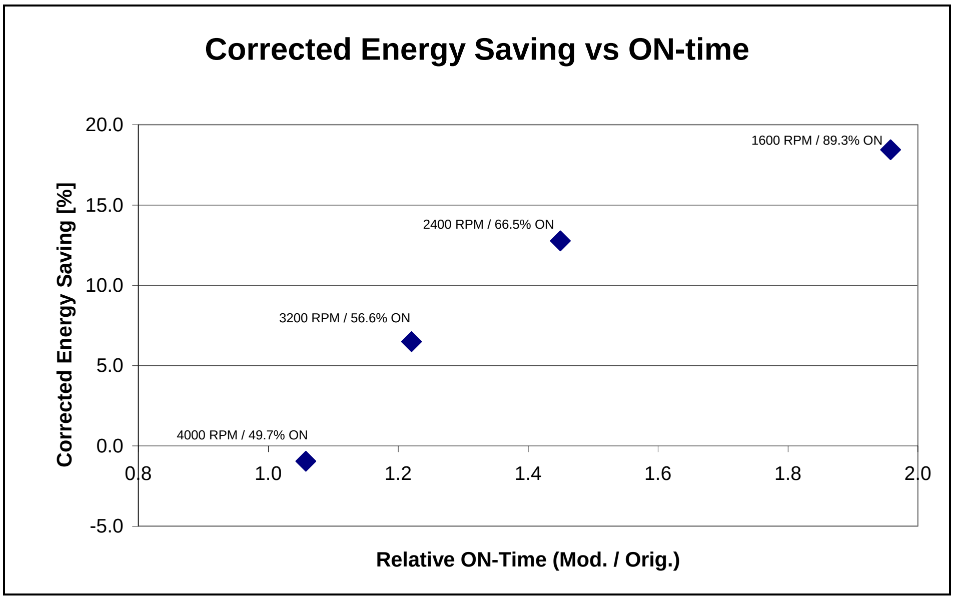

Fig. 15 Energy saving compared to the standard refrigerator for different relative ON-times

ON-time of 90%

The higher the relative ON-time of the compressor the more energy is saved. The lowest energy was consumed at 1600 RPM where the compressor was running nearly 90% of the time (the original refrigerator was running almost 50% of the time because it was very warm in the lab).

4.1.4. Best performance

27% less energy

The best performance of the modified refrigerator was achieved when run at 1200 RPM. This resulted in a ON-time of 69% compared to 26% for the original refrigerator (factor 2.7). In this configuration 27% less electrical energy was consumed by the modified refrigerator.

Lots of potential for more energy saving

It shall be emphasized that the energy saving of 27% was achieved, even though the modified refrigerator has a stand-by consumption of 1.2 W compared to 0.2 W for the original refrigerator. We see much potential for even more energy saving.

5. Conclusion

Small modifications

The results presented here show, that much energy can be saved by small modifications on a household refrigerator. The most important modification was the installation of a compressor with variable rotation speed which can be run at much lower speed when the refrigerator just has to hold its temperature. Thus, the compressor is almost constantly running. The higher efficiency is mainly due to the following factors:

Reasons for higher efficiency

- Less (energy intensiv) starting cycles
- Less internal losses due to lower flow rates
- Smaller and more constant temperature gradients between the cooling circuit and the inside of the refrigerator.

27% less energy

In direct comparison the modified refrigerator with its compressor running at just 1200 RPM consumes up to 27% less electricity than the original refrigerator running at 3000 RPM. Over the lifetime of the unit (about 15 years) this leads to financial savings of only about CHF 100.-. However, the global impact on the environment is significant.

Positive side effects

In addition to using less electricity the variable compressor is less loud when run at lower speed and can be run at very high speeds when „cooling bursts“ are necessary, for instance when warm goods are placed inside.

6. Next steps

Cost efficiency

We have shown that a compressor with variable rotation speed can lead to a significant reduction in energy consumption. In the next project phase it must be shown that this can be achieved in an economic way (without a large increase in production costs).

“Close to series” refrigerator

As a next step a „close to series“ refrigerator should be built with integrated compressor control. This refrigerator should then be tested to show that class A^{+++} can be achieved. A strong focus must lie on the optimization of manufacturing costs.

Refrigerator manufacturer as a partner

For this next phase it is essential to have a refrigerator manufacturer as a partner to make sure that we do not develop aside from the market. It is also essential to get the necessary technical information. A key player would be of interest because he could put more pressure on the compressor manufacturers and the market launch would have a much larger global effect.

Citations

[1] *Bush, E. und Josephy, B.* (2007) „Hintergrundinformationen: Mehr Stromeffizienz mit A++ Kühl- und Gefriergeräten“, topten.ch/energie schweiz, http://www.topten.ch/uploads/images/download-files/Hintergrund-informationenA++.pdf

[2] *Philipp, J.* (2000) „Optimierung von Haushaltskühlgeräten mittels numerischer Modellierung“, Dissertation der Fakultät Maschinenwesen der Technischen Universität Dresden, Forschungsberichte des Deutschen Kälte- und Klimatechnischen Vereins Nr. 65, Dezember 2000