Impact of aging on the energy efficiency of household refrigerating appliances

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Highlights

- The electrical energy consumption of a fleet of household refrigerating appliances is investigated over up to 25 years in an extensive measurement campaign.
- An aging model based on measurement data from real aged household refrigerating appliances is presented.
- This model indicates a significantly larger increase of the electrical energy consumption than literature models.
- Due to the aging, the average electrical energy consumption increases by 27 % after 16 years of operation.

Keywords

Household refrigerating appliances, Energy efficiency, Aging, Electrical energy consumption

Abstract

The parameters required to calculate the energy efficiency of household refrigerating appliances (i.e. refrigerators, freezers and their combinations) are determined by standard measurements. According to regulations, these measurements are carried out when the appliances are new. It is known from previous studies that various technical aging mechanisms can increase electrical energy consumption by up to 36 % over a product lifespan of 18 years. In order to determine the time dependence of the energy consumption of household refrigerating appliances, repeated measurements are carried out in this work. Eleven new appliances are examined under standard measurement conditions. After just two years of operation, an additional energy consumption of up to 11 % is determined. Furthermore, 21 older appliances that had previously been measured in new condition are tested again after up to 21 years of operation. For these older appliances, an average increase of energy consumption of 28 % is found. For individual appliances, the maximum increase is 36 %. An aging model is developed on the basis of these measurement results, which may help to predict the aging-related increase of energy consumption of household refrigerating appliances. This model shows an average increase in energy consumption of 27 % for an appliance age of 16 years. Supplemental performance tests of eight compressors do not show any significant aging effects related to these devices after two years of operation. Furthermore, measurements of the thermal conductivity of aged polyurethane foam test samples are carried out and an increase of its thermal conductivity of 26 % over a period of about three years is determined.

Nomenclature

a	Normalized energy consumption offset of the aging function
A	Surface (m^2)
A_a	Outer surface (m^2)
A_i	Inner surface (m^2)
A_{HIPS}	Average surface of the HIPS inner liner (m^2)
A_{PUR}	Average surface of the PUR foam (m^2)
A_{st}	Average surface of the steel case (m^2)
b	Time correction factor (a)
COP	Coefficient of performance
dE_i	Difference between the measured electrical energy consumption of two individual measurements (kWh/d)
d_{HIPS}	Material thickness of the HIPS inner liner (mm)
d_{PUR}	Material thickness of the PUR foam (mm)
d_{st}	Material thickness of the steel case (mm)
dT_i	Difference between the measured storage temperatures of two individual measurements (K)
E	Electrical energy consumption (kWh/d)
$E(\tau)$	Electrical energy consumption at the time τ (kWh/d)
E_0	Electrical energy consumption at the first measurement (kWh/d)
E_P	Corrected electrical energy consumption immediately after production (kWh/d)
g	Parameter of the aging model
k	Heat transfer coefficient ($W/(m^2 \cdot K)$)
$k \cdot A$	$k \cdot A$ value (W/K)
P	Mechanical drive power (W)
P_{el}	Electrical drive power (W)
P_{ecs}	Power of the electrical control system (W)
$\dot{Q}_0$	Heat flow in the evaporator (W)
$\dot{Q}_{cab}$	Heat flow into the cabinet (W)
r	Initial aging rate of the blowing agent (%)
x	Correction factor
α_a	Outer heat transfer coefficient ($W/(m^2 \cdot K)$)
α_i	Inner heat transfer coefficient ($W/(m^2 \cdot K)$)
δE	Total uncertainty of the energy measurement (%)
δE_e	Uncertainty of the energy measurement system (%)
δE_t	Contribution of the temperature measurement uncertainty to the energy measurement uncertainty (%)
δT_t	Temperature measurement uncertainty (K)
Δe_{ir}	Annual increase rate of electrical energy consumption (%)
ΔCOP	Improvement of the COP (%)
ΔE	Increase of the electrical energy consumption

$\Delta E_0(\tau)$	Preliminary aging model
$\Delta E_p(\tau)$	Aging model
ΔT	Temperature difference (K)
η_m	Motor efficiency (%)
λ	Thermal conductivity (W/(m·K))
λ_{HIPS}	Thermal conductivity of HIPS (W/(m·K))
λ_{PUR}	Thermal conductivity of PUR foam (W/(m·K))
λ_{st}	Thermal conductivity of steel (W/(m·K))
τ	Time (a)
τ_c	Time of an operating cycle (h)

Indices

0	Related to the electrical energy consumption during the first measurement
p	Related to the electrical energy consumption immediately after production

1. Introduction

The electrical energy consumption of household refrigerating appliances (i.e. refrigerators, freezers and their combinations) has continuously decreased since the 1990s [1]. Although it is relatively small for individual household refrigerating appliances, the entire fleet makes up a large proportion of the total electrical energy consumption because of the almost complete market penetration and year-round operation of these appliances. The launch of the EU energy label in 1994 accelerated this process further. With this label, it is possible for the customer to assess the energy efficiency of an appliance in relation to its energy consumption and the usable storage volume. On average, 13.4 % of the electrical energy consumption of private households in the OECD member states is caused by cooling and freezing food [2]. In Germany, this share was even 22.4 % in 2018 (cf. Figure 1), which corresponds to 5.4 % of the total national electrical energy consumption [3-5].

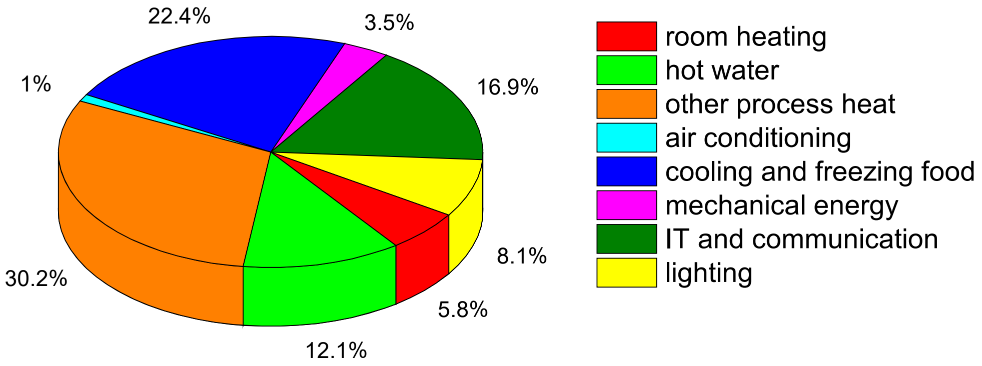

Figure 1: Distribution of the electrical energy consumption in private households in Germany [4].

Like all technical systems, household refrigerating appliances are subject to aging. Since the failure of individual components can lead to the failure of the entire system, individual components, such as compressor [6] or door hinges [7], are subjected to defined tests in order to predict their failure probability and thus ultimately the reliability of the refrigerating appliance. The typical contributions of the individual components to the total electrical energy consumption of household refrigerating appliances are described in the ASHRAE handbook as listed in Table 1 [8].

Table 1 – Typical contributions of the system components to the total electrical energy consumption of household refrigerating appliances [8].

system component	proportion of energy consumption
fan motor	2 to 10 %
external heater	0 to 6 %
defrost heater	4 to 10 %
wall insulation	45 to 55 %
door gasket region	25 to 30 %

In 1990, the Australian Consumers' Association investigated energy consumption data of household refrigerating appliances over a period of one year and did not find any increase due to aging [9]. In contrast, comparative studies with respect to CFC-free appliances by Elsner et al. from 2012 showed an increase of energy consumption of 25-36 % over a period of 18 years. The examined appliances were among the first CFC-free household refrigerating appliances to hit the market in 1994 and 1995, respectively [10-12].

A study commissioned as part of the development of the EU energy label regulation of 2019 mentions the insulation foam material, door gaskets, interior elements and compressor as primary causes for aging and assumes that aging could lead to an increase of energy consumption of 10 % over an estimated average operating time of 16 years, consisting of a primary operating period of 12-13 years and a secondary operating period of 3-4 years (e.g. in a garage) [13].

In his dissertation, Harrington examined the influence of various parameters on energy consumption. This includes the influence of temperature and humidity in the storage compartment, ambient temperature, evaporator defrosting, door openings, the general choice of the model and the influence of consumer behavior. However, he did not consider ageing of the product [14].

Based on a consumer survey with 706 participants, Hueppe et al. investigated the influence of consumer behavior on energy consumption in Germany. The study showed that 32.5% of the energy consumption was influenced by consumer behavior, e.g. door openings or choice of the installation site [15].

Technical properties of household refrigerating appliances, such as the energy consumption, are determined according to standards under laboratory conditions with a focus on comparability and reproducibility. Energy consumption measurements are carried out at standardized ambient temperatures mostly without user influence [7, 16-21] or with only little [22]. The ambient temperatures during these measurements are higher than the average room temperature in a kitchen. A study by Moretti in 2000 has shown that the impact of user influence on energy consumption can be compensated by a higher ambient temperature during standard measurements [23]. The real energy consumption in a household depends very much on the individual user [15], which can vary greatly from household to household [14].

Household refrigerating appliances essentially consist of a compression refrigeration cycle and an insulated cabinet. With respect to energy consumption, this demands a refrigeration cycle that is as energy-efficient as possible and the lowest possible heat flow entering the cabinet through the walls and the door gaskets. Consequently, the components which influence the energy consumption most need to be investigated with respect to changes over lifetime.

1.1. Theoretical calculation of energy consumption

The change of the electrical energy consumption of real household refrigerating appliances can be deduced from the change of the thermal conductivity of the polyurethane (PUR) foam. The energy consumption E of a household refrigerating appliance can be calculated by integrating the mechanical drive power $P(\tau_c)$ and the power of the electrical control system $P_{ecs}(\tau_c)$ over the time of an operating cycle:

$$E = \int \frac{P(\tau_c)}{\eta_m} d\tau_c + \int P_{ecs}(\tau_c) d\tau_c \qquad (1)$$

In the case of mechanical drive power, the motor efficiency factor η_m must be considered in the calculation. Figure 2 shows an example of the electrical drive power of three different appliances. The behavior is not uniform such that the theoretical calculation of the energy consumption is not straightforward.

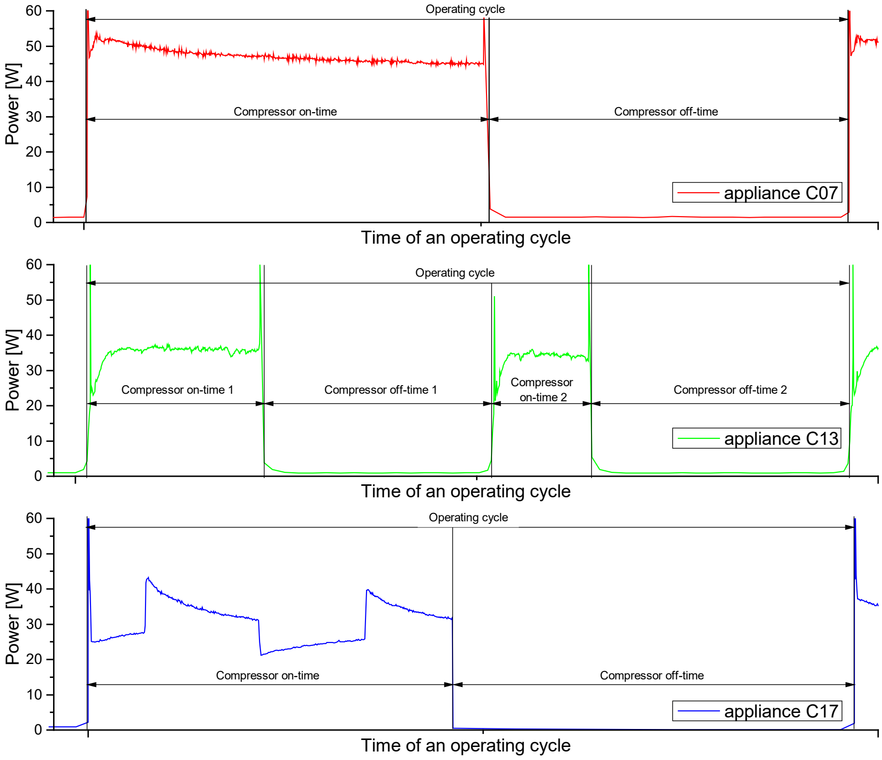

Figure 2: **Course of the electrical power over time for one operating cycle of three different appliances.**

Due to cyclical switching (on and off) of the compressor, the mechanical drive power is not constant during an operating cycle. It can be determined by dividing the heat flow absorbed by the evaporator $\dot{Q}_0$ by the coefficient of performance COP according to:

$$P = \frac{\dot{Q}_0}{COP} \tag{2}$$

The product of the heat transfer coefficient k, the average surface of the cabinet A and the mean temperature difference between the storage room and the ambient ΔT, yields the heat flow into the cabinet $\dot{Q}_{cab}$, which is balanced by $\dot{Q}_0$:

$$\dot{Q}_{cab} = k \cdot A \cdot \Delta T = \dot{Q}_0 \tag{3}$$

The product of the heat transfer coefficient and the average surface of the cabinet is summarized by the $k \cdot A$ value. The $k \cdot A$ value can be calculated from the heat transfer coefficient on the inside and outside of the cabinet, the outer and the inner surface of the cabinet and the average surface, material thickness and thermal conductivity of the respective materials:

$$\frac{1}{k \cdot A} = \frac{1}{\alpha_a \cdot A_a} + \frac{d_{st}}{\lambda_{st} \cdot A_{st}} + \frac{d_{PUR}}{\lambda_{PUR} \cdot A_{PUR}} + \frac{d_{HIPS}}{\lambda_{HIPS} \cdot A_{HIPS}} + \frac{1}{\alpha_i \cdot A_i} \tag{4}$$

The thermal conductivity of the PUR foam λ_{PUR} influences the heat flow into the cabinet $\dot{Q}_{cab}$ and increases over time. In order to relate the thermal conductivity to the energy consumption E, the exact cabinet geometry and structure, motor efficiency η_m, power of the electrical control system $P_{ecs}(\tau_c)$ and the COP of the refrigeration cycle must be known, which is usually only possible for a manufacturer's proprietary product.

1.2. Compressor

A reciprocating compressor is typically used in modern household refrigeration appliances. The aging behavior of compressors can be deduced from tribological studies of the relevant material pairings. For this purpose, samples of the material pairings (materials, compressor oil and refrigerant) are rubbed against each other in a test stand [24, 25]. Microscopic examinations of the artificially aged materials allow for conclusions to be drawn about the refrigerant flow during real compressor operation. It is expected that the damage caused by friction will lead to a leakage mass flow passing from the high pressure side to the low pressure side. As a result, the compressor has to compensate for this loss, which leads to an increase in relative running time. Research by Garland and Hadfield from 2004 shows an increase in relative running time from 30-39 % over a period of 15 years [25]. This corresponds to an increase of power consumption of ~ 30 % solely induced by compressor aging. The results of Elsner et al. [10] also showed an increase of the energy consumption of approx. 30 % after 18 years of operation, but this value was determined for entire household refrigerating appliances, including the aging of the cabinet wall insulation and the door gaskets. Hence the results of Garland and Hadfield appear to be overestimated.

Furthermore, electrolytic processes can cause copper ions from the materials inside the compressor housing to dissolve in the refrigerant-oil mixture and deposit at various locations in the compression refrigeration circuit. This so-called copper plating process, which has been studied since the 1950s [26], can lead to a reduction of mass flow, which entails to a reduction of cooling capacity and an increase of energy consumption. In the course of the conversion to CFC-free refrigerants between 1990 and 2007, further investigations were carried out [27]. In 2007, Kaufmann et al. proposed several measures to prevent copper plating [28]. In compressors currently used in household refrigerating appliances, copper plating only plays a minor role. For the next generation of modern refrigerants with a low global warming potential and their lubricants, studies of compatibility with the materials used in the compressor were carried out by Majurin et al., showing that some pairs may bear reliability risks [29].

Since a defect of the compressor always leads to a total failure of the entire household refrigerating appliance, accelerated life tests are carried out with compressors in order to estimate their life expectancy [30-33]. The actual long-term performance behavior of modern hermetic compressors over several years of real operating conditions has so far only been insufficiently investigated. Most manufacturers test their appliances immediately after production for a period of a few hours on fully automated test stands in order to identify production issues.

1.3. Door gaskets

In the ASHRAE handbook from 2010, the proportion of the heat flow entering the storage compartment through the door gaskets is listed to be 25-30 % of the total heat flow [8]. Because of the usual material composition of polyvinyl chloride with plasticizer, aging effects are also to be expected in the subsystem door gasket [34]. However, studies by Litt et al. from 1993 showed no clear influence on the energy consumption by exchanging old door gaskets with new ones [35]. Using numerical simulations, Kim et al. examined the heat transfer characteristics near the door gaskets and compared the results with experimental studies [36].

1.4. Wall insulation

With 45-55 % of the total energy consumption of household refrigerating appliances, the heat flow through the cabinet walls makes up the largest share [8]. The cabinet usually consists of a thin galvanized sheet steel layer of approximately 1 mm on the outside, an insulation with a thickness of 40-60 mm made of PUR foam and an inner liner made of high impact polystyrene (HIPS), which is approximately 0.6-2 mm thick

[37]. The basics of heat transfer in PUR foam were examined by Wagner in his dissertation [38].

Since the 1990s, the cabinet walls of household refrigerating appliances essentially consist of PUR which is foamed with cyclopentane as a blowing agent. Cyclopentane evaporates during exothermic reactions and thus cools the emerging PUR foam. A large number of reactions takes place in parallel during that foaming process. With respect to the aging process, the formation of carbon dioxide (CO_2) as a result of the reaction between water and isocyanate is crucial. Both cyclopentane and CO_2 serve as blowing agents and foam the PUR up. Immediately after the foaming process, the gas enclosed in the cells of the PUR foam essentially consists of these two gas species only. Due to composition differences between the cell gas and the ambient air, CO_2 diffuses out of the foam cells and nitrogen (N_2) and oxygen (O_2) diffuse into the foam cells. Since nitrogen and oxygen have a larger thermal conductivity than CO_2, the total thermal conductivity of the PUR foam increases over time. In most appliances, diffusion takes place through the inner liner made of HIPS, since the outer case is made of steel, which is impermeable for these gases. The diffusive exchange of the three gas species (CO_2, N_2 and O_2) takes place at different rates due to their varying diffusion coefficients, while cyclopentane diffusion is practically negligible [39-41].

Before 1990, CFC-11 was predominantly used as a physical blowing agent for PUR foam [42-44]. As water is not required for these reactions, no CO_2 is generated so that these older PUR foams are more resistant to aging than modern PUR foams. The increase of thermal conductivity of PUR foams used in household refrigerating appliances has been the subject of publications by Wilkes et al. [45-49] and Hueppe et al. [50], while Albrecht investigated PUR foams in the context of building construction [51]. Wilkes compared the thermal conductivity of PUR foams made with cyclopentane to PUR foams made with CFC-11. Over a period of three years, an increase of the thermal conductivity of 16.7 % was found. The results by Hueppe et al. [50] show an increase of 15.1 % over a period of 1.15 years, with significantly more modern PUR foams being examined.

To determine the quality of the insulation of the appliance housing, the reverse heat leak method [52-56], the use of heat flow sensors [53, 57, 58], the b-method [50] and the latent heat sink method [37] are described in the literature. The increase of the $k \cdot A$ value of a household refrigerator cabinet over time has until now only been investigated with the latent heat sink method. Paul et al. [37] found an increase of 6.1-11.3 % for the $k \cdot A$ value over a period of 14 months looking at four cabinets.

Aging mechanisms are also known in other refrigeration applications. In 2018, Capo et al. examined the aging of refrigerated transport equipment and showed that the overall insulation coefficient of nine different refrigerated vehicles increases by up to 65 % in the first twelve years. In the following 6 years, this value changed only slightly [59]. In principle, diffusion is much less problematic in the sandwich profiles used in refrigerated vehicles than in household refrigerating appliances, as the PUR foam in the sandwich profiles used for the vehicles is surrounded on both sides by a metal layer that acts as a diffusion barrier.

1.5. Energy consumption model

On the basis of Wilkes' results, Johnson in 2000 published a function that describes the annual increase rate of energy consumption (Δe_{ir}) of household refrigerating appliances [60]:

$$\Delta e_{ir} = r \cdot \left(\frac{20-\tau}{20}\right)^{x} \tag{5}$$

In this equation, r is the initial aging rate of the blowing agent, τ the appliance age and x a correction factor depending on the blowing agent. Johnson revised this model in 2004 and depicted the increase of energy consumption graphically. This function attains a limiting value of 21 % for an appliance age of 20 years [61].

Although there are some data on the increase of the energy consumption of refrigeration appliances with age, there is no systematic investigation about the origin of this increase and especially there is no comprehensive model which combines all those effects and allows to describe the average loss of electrical energy efficiency over age. It is therefore the aim of this paper to complement the available information with new and systematically gathered data and to incorporate them into a generalized model for the age-dependent efficiency of refrigeration appliances.

2. Test setup

All measurements were carried out in climatic chambers with an ambient temperature fluctuation of ± 0.5 K and an air humidity of 50 %. As the employed measuring systems were modernized several times during the study period from 1994 to 2020, the system-related measurement uncertainty changed over this extensive period of time.

2.1. Methodology

To determine the aging behavior of household refrigerating appliances (i.e. refrigerators, freezers and their combinations), the electrical energy consumption of 21 appliances from different manufacturers and appliance categories [62] was measured after their production and repeatedly after several years of operation. The individual measurements were consistently carried out according to the standards applicable in the year of production. These are the standards DIN EN ISO 15502:2006

[16] in conjunction with DIN EN 153:2006 [63], DIN EN 62552:2013 [7] and the series of standards IEC 62552:2015 [17-19]. Furthermore, 11 new household refrigerating appliances were examined several times over a period of two years following the IEC 62552:2015 series of standards [17-19]. For better comparability of the results according to the various standards, a uniform ambient temperature of 25 °C was used for all measurements. In the supplemental material, Tables SM1 to SM32 list all appliances with the respective standards or test programs which were used during the measurements. All energy consumption results were interpolated to the respective compartment target temperatures as defined in the standards.

2.2. Temperature measurement

Temperatures were sampled by thermocouple differential measurements, where each measuring junction had its own reference junction in a separate ice water bath. In the period from 1994 to 2008, the measurement signal was recorded by an Acurex Cooperation system consisting of an Autodata Ten/5 datalogger and an Autodata 1016 scanner with a measurement uncertainty of ± 0.3 K. After 2008, the measurement signal of the thermocouples was processed by a combination of a pre-amplifier LTC1050 (Linear Technologies) with adjusted gain of 1000 and an analog-to-digital converter system OMB DAQ 55/56 (Omega Technologies), limiting the offset drift to ± 0.025 K. By calibrating each thermocouple individually and applying a polynomial correction, the measurement uncertainty was reduced from ± 1 % x ΔT to ± 0.5 % x ΔT.

2.3. Energy measurement and power supply

Until 2012, the system GTU 0610 from ASEA BROWN BOVERI was used with a measurement uncertainty of ± 1 %. Since 2012, a single-phase large-range energy meter of the type EZI 1 from ZES Zimmer Electronic Systems was used, resulting in a reduced measurement uncertainty of ± 0.5 % and a better resolution.

The GTU 0610 was inserted between the power supply and the appliance during the test (measurement site) via the conventional 2-wire connection method. Using the new EZI 1 system, the appliances were equipped with a 4-wire connection allowing for a separate current and voltage measurement. Both systems have a pulse output, each pulse corresponds to an energy quantity of 2812.5 Ws for GTU 0610 and 144 Ws for EZI 1. Each pulse was recorded in time and date. The final energy consumption follows from the summation of the pulses during the relevant time period.

In the early years of this investigation, the supply voltage for the test appliances was conditioned with a voltage stabilizer Skz D 241102 from Siemens. From 2012 onwards, an electronic power source ACS-6000-PS from HBS Electronic was used.

2.4. Measurement uncertainty

Table 2 shows the specific measurement uncertainty of the various measurement systems used in this study.

Table 2 – Measured properties and their uncertainties.

Measured quantity	System	Time period	Measuring device	Uncertainty
Temperature	Acurex	1994 to 2008	Thermocouples	± 0.3 K
	DAQ	2008 to 2020	Thermocouples	± 0.1 K
Energy consumption	GTU	1994 to 2012		± 1.0 %
	EZI	2012 to 2020		± 0.5 %
Power supply	Siemens	1994 to 2012		± 1.0 %
	ACS	2012 to 2020		± 0.1 %
Time		1994 to 2020	Personal computer	± 0.1 s/day

Due to the interpolation of energy consumption measurements at two temperatures to a target temperature, the temperature measurement uncertainty also influences the total measurement uncertainty of energy consumption, cf. Figure 3. This influence was determined individually for each interpolated measuring point by:

$$\delta E_t = \sqrt{\sum \left(\frac{dE_i}{dT_i}\right)^2 \cdot \delta {T_t}^2} \tag{6}$$

In this equation, δE_t is the uncertainty of the energy measurement due to the uncertainty of the temperature measurement δT_t, dE_i is the difference between the measured energy consumption of the two individual measurements and dT_i the difference between the measured storage temperatures of the two individual measurements. The total uncertainty of the energy measurement δE is given by the sum of the uncertainty of the energy measurement system δE_e and the interpolation uncertainty δE_t:

$$\delta E = \delta E_e + \delta E_t \tag{7}$$

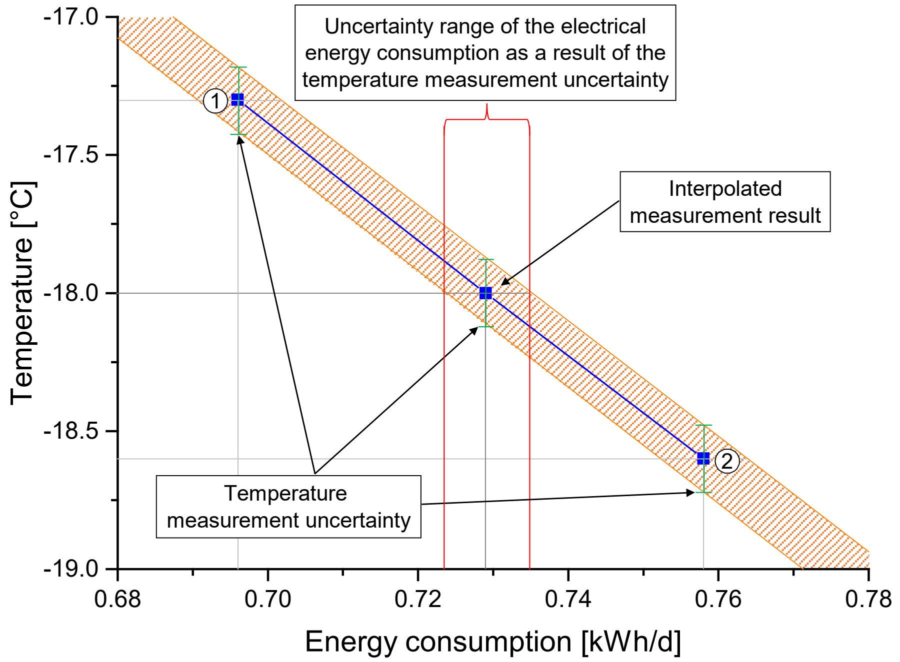

Figure 3: **Influence of the temperature uncertainty on the measurement uncertainty of the electrical energy consumption (example).**

2.5. Thermal conductivity of aged PUR foam samples

As a continuation of the measurements by Hueppe et al. [50], further values of the thermal conductivity of PUR foam up to an age of 2.76 years were determined in this work. The same measurement setup and methodology was used as in the original study [50].

2.6. Coefficient of performance of the compressor

Compressor measurements were carried out according to DIN EN 13771-1:2003 [64] with a calorimeter test stand (method A). The compressors were measured at the beginning of the study and then installed in eight appliances (cf. supplemental material Tables SM33 to SM40). After 2.00-2.17 years of real operation, during which the electrical energy consumption of the appliances was regularly measured, the compressors were removed and studied again. The COP was determined from the electrical drive power P_{el} and the heat flow in the evaporator $\dot{Q}_0$. The measurement accuracy of the heat flow was ± 0.3 %, that of the electrical drive power ± 0.1 % and the resulting COP uncertainty was ± 0.4 %.

3. Results

To determine the influence of aging on the electrical energy consumption of household refrigerating appliances, standard measurements were carried out. With these data, a model was created that describes the change of energy consumption depending on the age of the appliance.

The energy consumption at the production date cannot be derived from the value on the energy label as this is not the true value of an individual appliance. Due to e.g. manufacturing tolerances, the energy consumption stated on the energy label may deviate by up to 10 % from the real energy consumption of a specific appliance [62]. Because it was not possible to measure the energy consumption immediately after manufacturing, an estimate of this value had to be extrapolated from the existing data and information on the production date in order to create a consolidated aging model. For this purpose, a preliminary function was created to normalize the energy consumption of the first measurement. The aging function is an average of 32 appliances of different types. At present, it is not possible to determine an aging function for individual appliance models, as the available data for such a purpose are insufficient.

3.1. Measurement results

In a first step, each individual measuring point $E(\tau)$ of the interpolated energy consumption was divided by the energy consumption at the time of the first measurement E_0, creating a normalized function of appliance age τ:

$$\Delta E_0(\tau) = \frac{E(\tau)}{E_0} \qquad (8)$$

The results of 100 measurements standardized in this way are shown in Figure 4. A detailed list of the results for each of the 32 appliances can be found in the supplemental material (Tables SM1 to SM32).

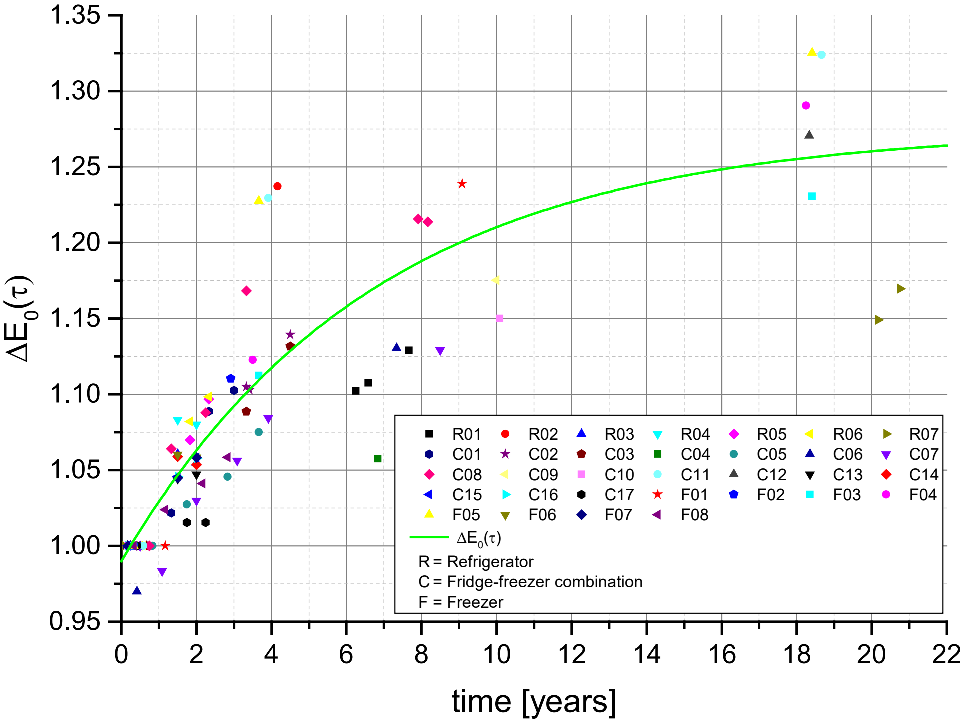

Figure 4: **Normalized energy consumption (symbols) and preliminary aging function (line).**

3.2. Aging function

Using measurement data, a preliminary aging function with the reference point of the first measurement was generated on the basis of an error function:

$$\Delta E_0(\tau) = g + a \cdot \left[1 - \mathrm{e}^{-\left(\frac{\tau}{b}\right)}\right] \tag{9}$$

Its parameters a, b and g were adjusted by minimization of the root mean square (RMS) difference between the measured energy consumption and the function. This resulted in a course that is depicted in Figure 4, cf. supplemental material for its parameter values (Equation SM1). Since the preliminary aging function shown in Figure 4 relates to the first measurement that was carried out in an already aged appliance state, it starts with a value of $g_0 = 0.990$ due to aging processes in the PUR foam, which begin immediately after production.

Using the preliminary aging function, it can be extrapolated to the hypothetical energy consumption at the production date of the appliances with:

$$E_p = E_0 \cdot \left[1 - \left(\Delta E_0(\tau) - \Delta E_0(\tau = 0)\right)\right] \tag{10}$$

This correction was applied to all data sets. As a result, the data points of the normalized energy consumption in Figure 5 shift slightly upwards.

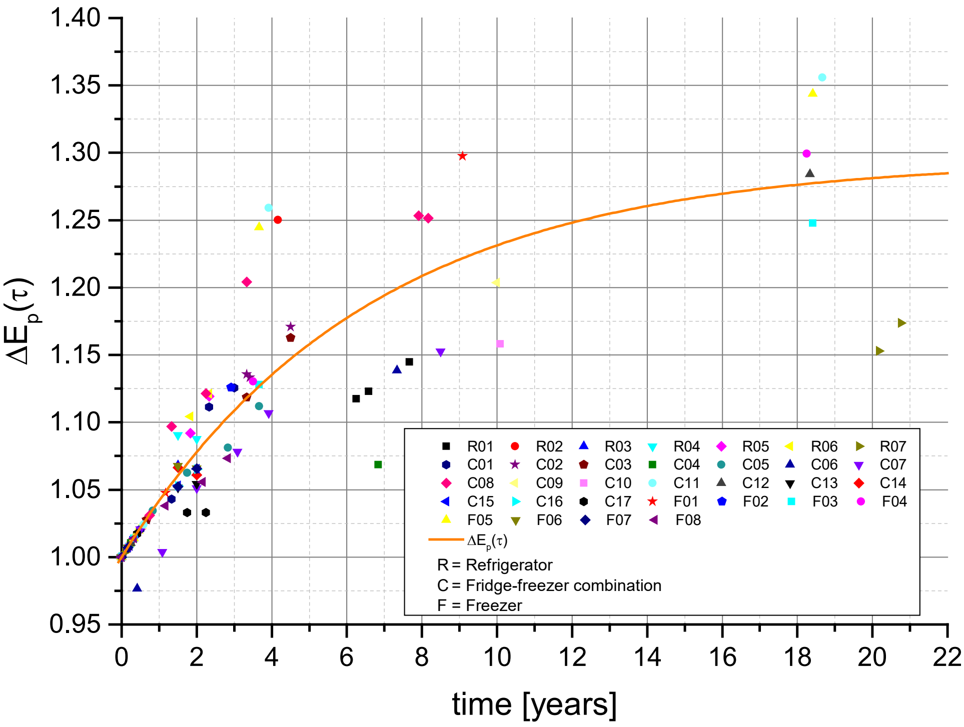

Figure 5: **Corrected energy consumption (symbols) and consolidated aging function $\Delta E_p(\tau)$ (line).**

The curve fitting procedure was repeated with the new standardized energy consumption data set, yielding the consolidated aging model, cf. Figure 5:

$$\Delta E_p(\tau) = 1 + 0.295 \cdot \left[1 - \mathrm{e}^{-\left(\frac{\tau}{6.517}\right)}\right] \tag{11}$$

3.3. Thermal conductivity measurements of PUR foam samples

As shown in Figure 6, the thermal conductivity λ of the PUR foam samples increases from the initial 19.5 mW/(m·K) by 26 % to 24.6 mW/(m·K) over a period of 2.76 years. Due to the different diffusion coefficients of the gas species CO_2, N_2 and O_2, mass transport takes place at different rates [38]. The composition of the gas species changes over time and with it the conductive heat transfer, which entails a slightly decreased thermal conductivity of the PUR foam during the first ~ 0.27 years after production.

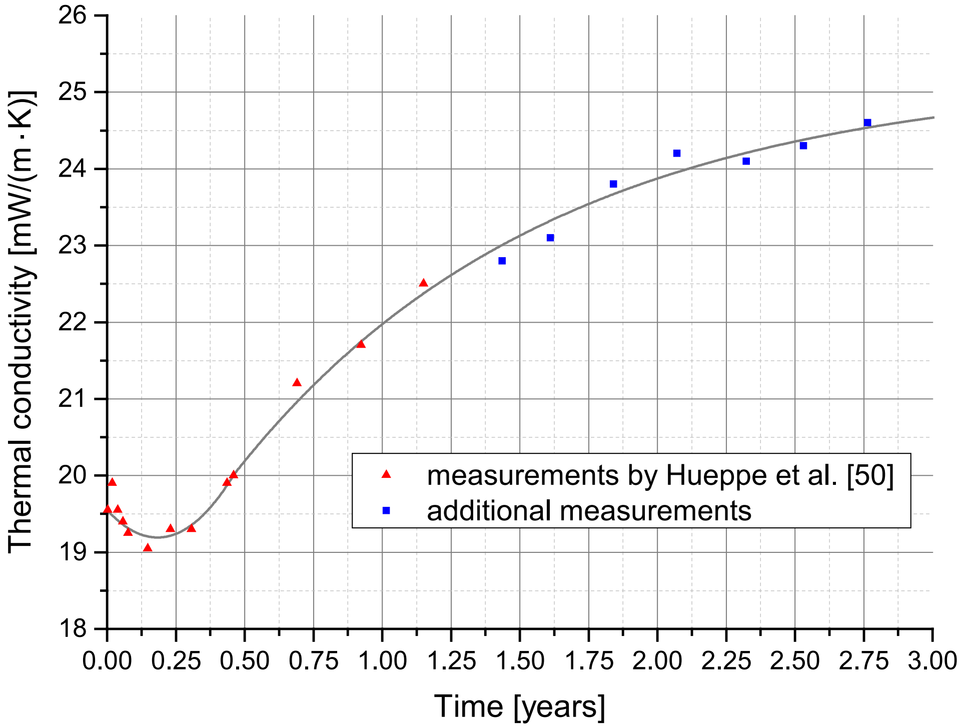

Figure 6: **Thermal conductivity measurements of PUR foam samples (symbols) and guide to the eye (line).**

3.4. Calorimeter measurements

The results of the calorimeter measurements are shown in Table 3. The COP tends to improve slightly over the period under review. Four compressors displayed a small improvement of the COP, three had nearly no change and only one device slightly deteriorated by -1.5 %. Overall, an average improvement of the COP of 0.9 % was found for the eight examined appliances. Based on these results, it can be assumed that there is a negligible influence on the aging behavior of household refrigerating appliances.

Table 3 – Results of the calorimeter measurements.

	Refrigerator brand	Refrigerator type	Compressor type (Secop)	Operating time (years)	COP_1	COP_2	ΔCOP
R03	Siemens	KI81RAD30	DLX4.8KK	2.00	1.77	1.83	3.4 %
R08	Siemens	KI81RAD30	DLX4.8KK	2.17	1.76	1.84	4.2 %
R09	Siemens	KI81RAD30	DLX4.8KK	2.17	1.76	1.75	-0.1 %
Average over all DLX4.8KK compressors				2.11	1.76	1.81	2.5 %
C18	Bosch	KIS86AF30	DLX7.5KK	2.17	1.98	1.99	0.2 %
C19	Bosch	KIS86AF30	DLX7.5KK	2.17	1.98	1.98	0.1 %
Average over all DLX7.5KK compressors				2.17	1.98	1.98	0.1 %
F06	Siemens	GS36NVW3V	HZK95AA	2.00	1.93	1.96	1.4 %
F09	Siemens	GS36NVW3V	HZK95AA	2.17	1.95	1.92	-1.5 %
F10	Siemens	GS36NVW3V	HZK95AA	2.17	1.93	1.93	0.1 %
Average over all HZK95AA compressors				2.11	1.93	1.93	0.0 %
Average over all compressors				2.13	1.88	1.90	0.9 %

4. Discussion

The present data clearly show that the increase of electrical energy consumption is most pronounced in the first five years after production. After the average operating time of a household refrigerating appliance of 16 years [13], there is an increase of energy consumption of 27 %. For the primary operating time of 12-13 years the increase is about 25 %. In the case of significantly older appliances, the further increase of energy consumption is negligible.

Since the appliances examined in this study are of different construction type and production processing quality, their aging results are scattered. Nonetheless, they essentially follow the mathematical course described in this paper. The largest individual data sets are available for the two appliances C07 and C08, each with six measuring points, which is sufficient to adjust the aging function accordingly. As can be seen in Figure 7, the measured energy consumption follows the course of the aging model given by equation 11.

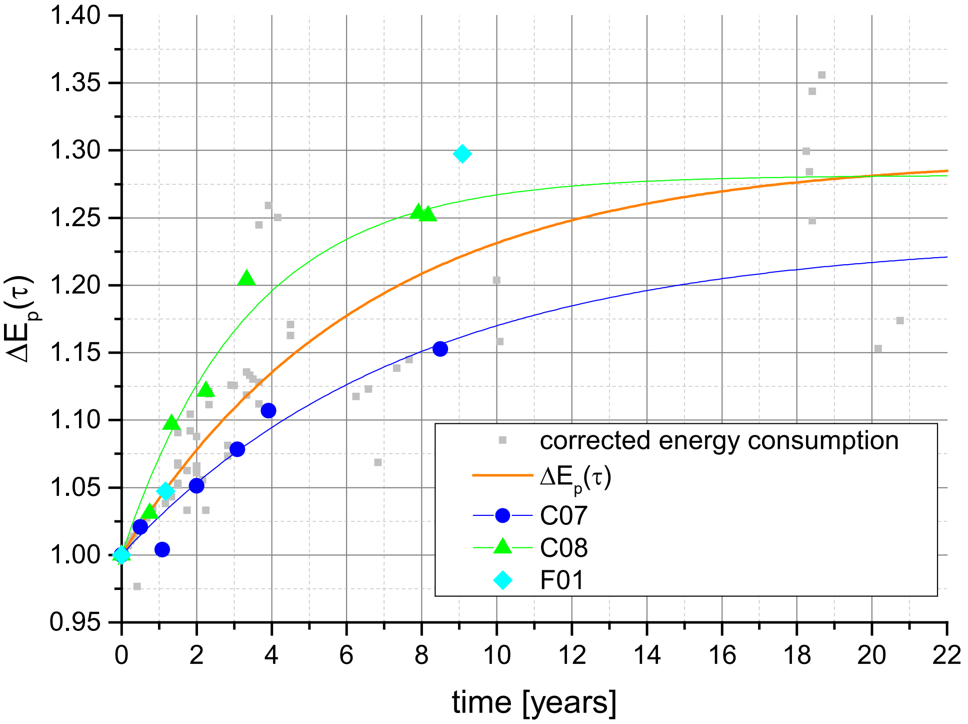

Figure 7: **Comparison between individual appliances C07, C08 and F01 and the average aging function.**

Another appliance that stands out is F01. The aging of this appliance led to an increase of 30 % with respect to energy consumption in just nine years. The reason for this is the missing diffusion barrier in parts of the outer housing, cf. Figure 8.

Figure 8: **Missing diffusion barrier at the cabinet of appliance F01.**

A comparison of the present aging model with other literature models is shown in Figure 9. Compared to the model of Johnson [52], a significantly larger increase of energy consumption was observed in this study. The Johnson model is based on the work by Wilkes [45-49], who measured the thermal conductivity of PUR foam samples over a period of 13 years, i.e. their aging function is an extrapolation beyond that point in time. Furthermore, this model assumes aging of the PUR foam only.

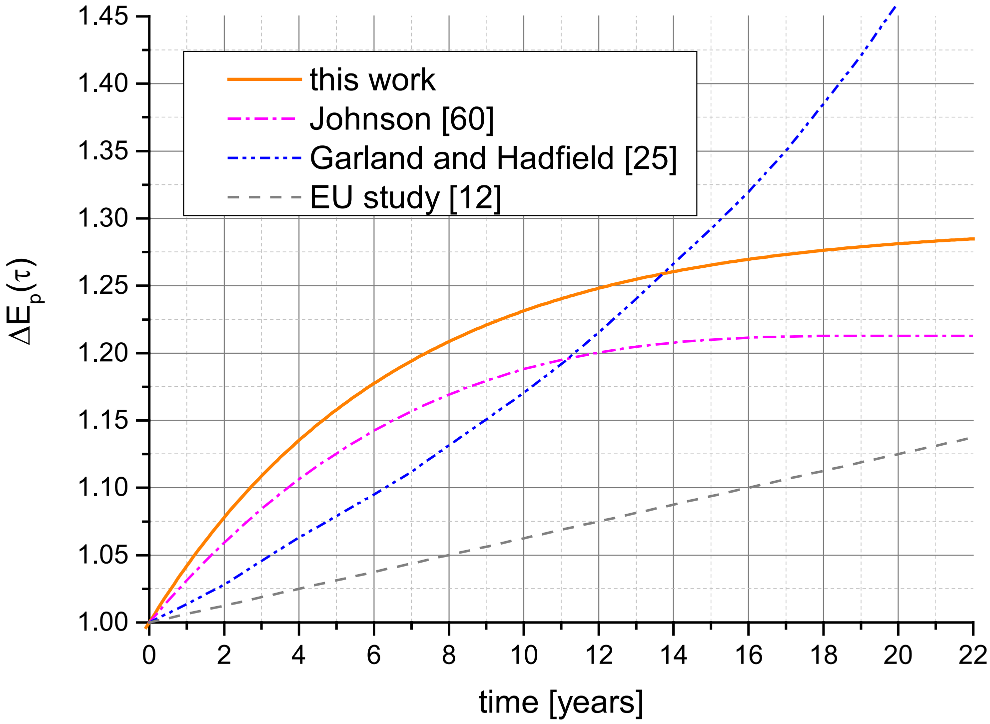

Figure 9: **Comparison of different aging models for electrical energy consumption.**

The study of Garland and Hadfield [25] reports a different function for the increase of energy consumption, cf. Figure 9. During the first 14 years, the model values are below the present data, but increase to significantly higher values for an appliance age over 14 years. In the underlying tribological investigation, a metal ball was rolled over a metal plate in a refrigerant-oil environment. This model is greatly simplified and limited to the compressor as the sole source of aging in a household refrigerating appliance.

In practice, no significant change of the compressor COP was found during the calorimeter measurements performed in this study. Essentially, this is likely to be due to better sealing valves and running-in of the bearings in the compressor. In addition, it is difficult to deduce the aging of household refrigerating appliances by solely observing the relative compressor run time. Because it indicates the ratio of the compressor on-time to the total time of a compressor cycle, the relative runtime might not change over the course of time, while both of the absolute values will do so in most cases.

The results of this study show that a 10 % increase of energy consumption over a period of 16 years as assumed in the EU study [13] is a significantly too low estimate, also when compared to the other aging models from the literature.

A direct comparison of the increase of energy consumption with the increase of the thermal conductivity of the PUR foam is shown in Figure 10. The data on the thermal conductivity from the work of Albrecht [51] and the present thermal conductivity measurements were also normalized in this diagram to the first measuring point of the data sets and they differ significantly from each another. This is essentially due to the different technical fields of application of the examined PUR foams.

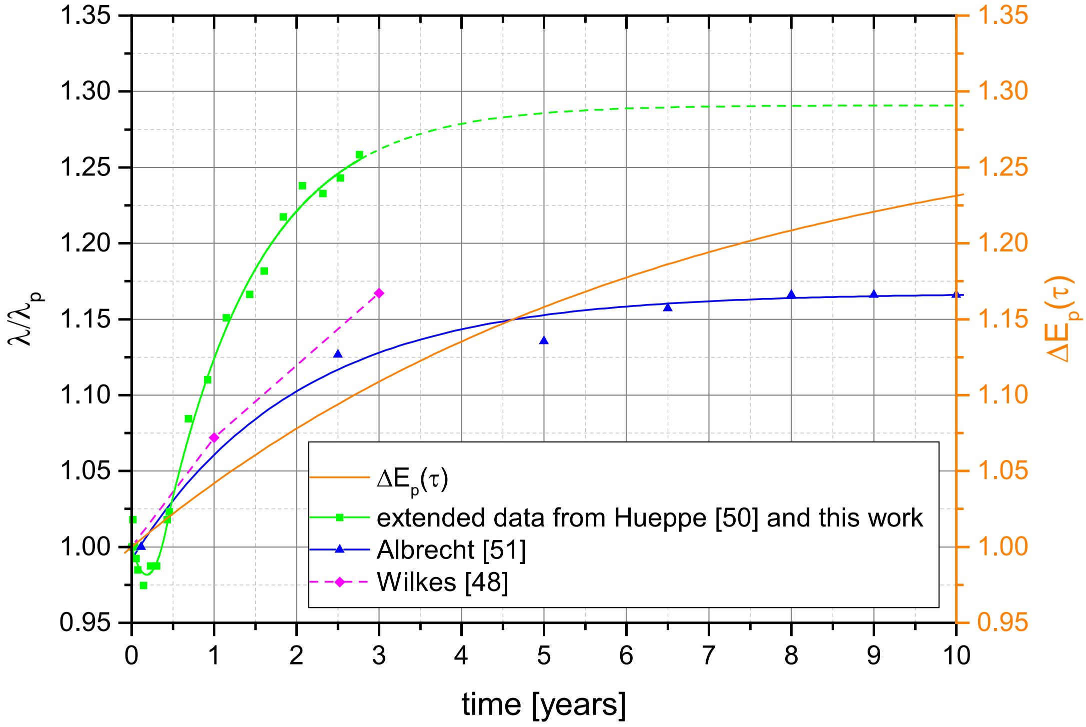

Figure 10: **Comparison of the aging model with the thermal conductivity increase of the PUR foam.**

With the additional measurements of the thermal conductivity carried out in this study, the aging process of the PUR foam can be better quantified. Approximately for five years after production, the thermal conductivity will rise and assume a limiting value of 25.2 mW/(m·K), which is an increase of ~ 29 % compared to the thermal conductivity at the time of production.

The thermal conductivity data published by Hueppe et al. [50] and in this study are significantly higher than those of Wilkes [48]. Since the data published by Wilkes are based on a foam made with CFC-11, a direct comparison of the two data sets is only possible to a limited extent.

In addition to the increase of the energy consumption due to technical aging that is addressed in this paper, the individual user behavior does influence the real energy consumption of household refrigerating appliances, as described by Harrington [14], Hueppe et al. [15] and Moretti [23]. In households with a high user induced heat load, the relative increase of the energy consumption due to technical aging will therefore be lower than in households with only a few door openings.

5. Conclusions

An aging model was derived from a solid data base of 100 electrical energy consumption values from a total of 32 appliances that were run under real operating conditions. It is the first function of its kind that was developed on basis of to true electrical energy consumption data. Older predictions of energy consumption derived from data on individual system components show significant differences to the aging model described in this study.

A 27 % increase of the energy consumption over an average operating time of a household refrigerating appliance of 16 years is shown. For extremely old appliances with an age of around 20 years, the energy consumption increases by up to 28 %. The aging model describes the average increase of the energy consumption of 32 different appliances. In the first three years, the difference between individual measurement points and the average aging function is within ± 5 %. As the measured values are scattered due to different production processing quality, design, size and other parameters, the increase of energy consumption in the later years of the appliances (older than 15 years) can deviate from the aging model by up to ± 15 %.

These findings should sensitize the stakeholders (manufactures, consumer organisations, standardisation bodies and legislators) for aging processes related to household refrigerating appliances. It is now possible to better determine the economic and energetic replacement time of the appliances for the customer and the overall economic impact caused by aging household refrigerating appliances.

In the coming years, further measurements will be carried out on the appliances that have been running for two years during this study. Furthermore, the currently poor data situation for an appliance age between 10 and 18 years has to be improved by additional measurements on older appliances. These data will help to render the aging model more precise.

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