



Impact of room temperature on energy consumption of household refrigerators: Lessons from analysis of field and laboratory data



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HIGHLIGHTS

- Measured performance of 111 laboratory & 235 home refrigerators is analysed.
- The effect of room temperature on energy consumption is investigated.
- Repeatable effects are found for different types of refrigerators.
- Universal empirical relationships for estimating energy consumption are developed.
- Approach allows modelling the effects of room temperature with minimal data input.

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ABSTRACT

Refrigerators are a common appliance in developed and emerging economies around the world. These appliances consume significant energy globally and improving their efficiency is an important aspect of future climate change mitigation. It is widely understood that the energy consumption of household refrigerating appliances is strongly influenced by room temperature and many analysts have identified ambient temperature as the most important factor in normal use. Room temperature has two main effects on the energy consumption of refrigerating appliances. Firstly, the temperature difference between the compartment and the room dictates the heat gain into the appliance through the wall insulation and door seals. A second effect is that a change in room temperature affects the condensing temperature. An increase in room temperature reduces overall refrigeration system efficiency by increasing the difference between the evaporating and condensing temperature. This paper examines laboratory data for 111 appliances where energy consumption is measured at four ambient temperatures from 10 °C to 40 °C. Field data for 235 appliances in homes is also examined. This is more complex to analyse, but it does provide useful information on underlying energy changes due to changes in room temperature during normal use. This paper determines the ratio of energy at 16–32 °C (energy conditions in IEC62552-3) and explores the shape of the energy curve at intermediate temperatures in order to develop a generalised energy curve as a function of temperature for the refrigerating appliances measured. The field data gave highly comparable shape data to that measured in the laboratory. The results provide a useful method to estimate the likely power consumption of different appliance types under a wide range of operating conditions, even where limited data is available.

1. Introduction

Refrigerators are ubiquitous appliances, with most households in developed countries having at least one, while there is rapid growth in ownership in developing countries [1,2]. Global sales of new refrigerators is around 150 million units a year [3,4] and the global stock in 2009 was estimated to be around 1.6 billion household refrigerating appliances [5]. These appliances are estimated to consume as much as

6% of global electricity [6] and improving their efficiency is an important aspect of future climate change mitigation. An important first step in the development of suitable energy policies to reduce energy consumption is the understanding of key drivers of energy consumption.

The vast majority of refrigerating appliances in service globally use the vapour compression cycle as this is the lowest cost and most efficient technology currently available for these appliances [7]. While it is

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widely understood that the energy consumption of household refrigerating appliances is strongly influenced by room temperature, there is little data or analysis into the impacts that changes in room temperature have on the energy consumption of these appliances, especially during normal use. Early research into refrigerator energy consumption identified that ambient temperature was a key driver of energy consumption [8–12]. This has been confirmed in many recent studies, which conclude that room temperature in which the appliance operates is the most important factor that impacts on energy consumption in conditions of normal use [13–20]. The main research question to be addressed is how can the changes in energy consumption of refrigerating appliances that are likely to be experienced under conditions of normal use be estimated from existing data sets and measurements without the need for extensive testing and complex additional measurements.

One possible approach is simulation. The literature has many examples of simulation of the energy consumption of household [14,21–26] and many of these models can estimate the energy consumption of a specific refrigerator in different ambient temperatures [27–29]. However, these simulation models are generally intended for use by engineers to improve and optimise the overall design of household refrigerators and the components that they use. These models require a lot of detailed engineering information about the design and construction of each appliance and its components and they use complex numerical approaches such as Computational Fluid Dynamics. The level of information required is not readily available and much of it is certainly not in the public domain. These types of models, while absolutely essential for product design and optimisation, have limited applicability in the development of broader energy policies and are generally not suitable for the estimation of energy consumption during normal use.

Test procedures are also another possible source of information. Until recently, most test procedures around the world for refrigerating appliances only measured energy of refrigerating appliances at a single ambient temperature. In the past, many test procedures specified an elevated room temperature for energy determination in order to compensate for the lack of user interactions during the test [8,10]. This means that reliable and accurate energy consumption data at different ambient temperatures is very limited globally. While refrigerators are a thermally dynamic appliance, documenting generic responses to changes in room temperature has not been undertaken previously in a way that can inform policy makers and analysts to help them understand how the energy consumption of these appliances varies in the field. In 2015, the International Electrotechnical Commission (IEC) Standard IEC62552-3 was published [30]; it set out a new global approach to energy consumption measurement, including energy tests at 16 °C and 32 °C. The pool of available data should expand as countries adopt the new IEC test method.

At this stage there is still a paucity of laboratory data on how refrigerating appliances typically respond to room temperature; this aspect of energy consumption is rarely published by suppliers as there is no obligation to do so under programs like energy labelling. Around the world there have been many campaigns that measure the energy consumption of refrigerating appliances during normal use in homes and offices. However, this data is complex because changes in energy consumption in response to room temperature, additional energy due to user interactions and additional energy associated with automatic defrosting are all mixed up together [31–35]. These types of studies in the past have been unable to explicitly take into account and separate the impact of changes in room temperature at each site.

Refrigerators are the most commonly regulated product for energy efficiency of any appliance or piece of equipment, with some 75 countries having 185 separate program measures for these appliances in 2013 [36]. The shortcomings in historical test procedures means that products are often measured and rated at conditions that are far from normal use. Therefore, products may be optimised for operating

conditions that do not reflect normal use and the estimated energy consumption from test procedures is usually inadequate for estimating energy costs for consumers and energy saving potential.

Detailed analysis of data from compressor manufacturers reveals that the change in the coefficient of performance (COP) for most products is very linear with changes in condenser temperature, as expected. However, an unexpected finding is that the absolute slope of COP for most compressors is very similar, regardless of the rated COP. This means that real compressor COP does not strictly follow theoretical Carnot COP for changes in condensing temperature. This is valuable background to understanding the analysis results in this paper.

There is a lack of information in the public domain that sets out the likely response of household refrigerating appliances to changes in room temperature, even though there is widespread understanding that the energy consumption of these appliances is sensitive to room temperature. This is a critical gap in the current knowledge as this type of information is important for the development of sound energy policies and it is crucial for forecasting energy demand into the future. The findings documented in this paper will provide a robust technical basis for making improvements to energy policies such as energy labelling and minimum energy performance standards, as well as providing a more credible basis for converting data measured in a test laboratory into more realistic estimates of energy consumption in the field. This will assist in energy forecasts and projections as well as large scale modelling of the energy consumed by these appliances into the future.

The aim of this paper is to provide a clear understanding of how refrigerating appliances operate across a range of temperature conditions that are likely to be encountered in normal use. This is achieved by examining the steady state power consumption as a function of room temperature for a wide range of refrigerating appliances both in the laboratory and in homes to provide rigorous generic relationships between temperature and power consumption for a wide range of product types. Previous studies have only covered a limited number of appliances, types and operating conditions and have not provided generic functions of the impact of temperature on energy across a large temperature range. Analysis in this paper provides confidence that the behaviour of many refrigerating appliances is consistent and can be generalised, which is an important expansion of our understanding of their energy consumption during normal use. The paper also provides practical tools to translate the energy consumption measured under different test procedures to a more generic function of steady state power versus ambient temperature for most normal use conditions. It therefore provides policy makers and analysts with a set of quantitative tools that could lead to improvements in policy development and energy forecasts, even where limited data is available, which would lead to improved energy efficiency and reduced energy consumption during normal use. It is based on measured data for a large number of appliances in the laboratory and in homes, which provides a unique insight into the energy consumption of refrigerators across a wide range of room temperatures.

2. Theory

2.1. Heat transfer into a refrigerating appliance

The heat gain through the walls of a refrigerator (including all sides exposed to ambient air and door seals) is a function of the insulation effectiveness (thermal transmittance or U value), surface area and the overall temperature difference between the internal compartment temperature and the room air temperature surrounding the refrigerator. When considering a specific refrigerator, the U value and the surface area are both fixed at the time of design and manufacture, so the heat gain through the appliance walls into each compartment is a linear function of the temperature difference (external temperature minus internal temperature). Often there are several compartments, each with a different U value and each with a different operating temperature that

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