New Energy Test Procedures for Refrigerators and Other Appliances

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ABSTRACT

Many innovations in refrigerator design rely on microprocessors, sensors, and algorithms to control automatic defrost, variable speed, and other features. Even though these features strongly influence energy consumption, the major energy test procedures presently test only a refrigerator's mechanical efficiency and ignore the “software” aspects. We describe a new test procedure where both "hardware" and "software" tests are fed into a dynamic simulation model. A wide range of conditions can be tested and simulated. This approach promotes international harmonization because the simulation model can also be programmed to estimate energy use for the ISO, DOE, or JIS test. The approach outlined for refrigerators can also be applied to other appliances.

INTRODUCTION

Nearly all major, energy-consuming appliances are now undergoing the conversion from electromechanical to electronic, digital control. Many appliances already rely on a microprocessor to control operation. Sensors are being added to help the microprocessor more precisely control the appliance as well as to provide new features. The result will be much more intelligent, flexible appliances that rely less on the user to select the most appropriate control strategy. New automobiles–the largest consumer appliance–typically have a dozen microprocessors, controlling everything from engine emissions to braking without the driver’s assistance (or even knowledge).

The shift from electromechanical to digital control offers hundreds of opportunities to operate the appliance in a more energy-efficient manner.[1] In a refrigerator, a microprocessor can adjust the defrost interval so that the energy-intensive defrost occurs only when actually needed, rather than after a specific number of hours of compressor operation. In a dishwasher, a dirt sensor coupled to microprocessor can select the optimum volume of hot water and the length of the wash cycle. In air conditioners, an array of sensors can control the speed of the compressor and fans to obtain the optimum heat and moisture removal so as to provide the maximum occupant comfort for the least energy. The great advances in energy efficiency during the next decade are most likely to be caused by the combination of microprocessor control and sensors than from mechanical improvements in compressors, insulation, heat exchangers, and motor design.

Unfortunately, the energy test procedures for these appliances have not kept pace with developments in appliance technology. The existing energy test procedures capture the performance of the mechanical features but mostly ignore microprocessor controls. By failing to credit the role that microprocessors play in appliance operation, the test procedures have discouraged appliance manufacturers from greater exploitation of the microprocessors' energy-savings potential. Worse, some less scrupulous manufacturers have used the microprocessor's intelligence to recognize when the appliance is being tested and to perform in a different, low-energy mode. General Motors, for example, designed the emissions control microprocessors in Cadillacs to perform differently when undergoing the Environmental Protection Agency's emissions tests than in normal operation.[2] (General Motors was fined forty-five million dollars for this action.). At least one refrigerator manufacturer and one air conditioner manufacturer have programmed the microprocessors in their products to perform differently in the laboratory tests than in normal operation. Other manufacturers will no doubt employ this strategy as appliance efficiency regulations become increasingly strict. To date, however, such actions are not technically illegal.

We believe that a completely new energy test procedure is necessary to parallel the revolutionary change in the way appliances operate. Furthermore, new tests must be created for all of the major, energy-consuming appliances.

There is also an international trend towards harmonization of energy test procedures. The World Trade Organization (WTO) considers test procedures that apply to a single country to be a non-tariff trade barrier. A single test procedure recognized throughout the world lowers manufacturers' costs and stimulates greater international trade. But there are also legitimate reasons for local test procedures where there are unusual operating conditions, such as climate or user preferences. We believe that the next generation of test procedures should be harmonized but should also provide for local conditions.

In this paper, we describe the elements of a new energy test procedure. Our goal is to create a test that encourages low energy use through innovative combinations of hardware and software. We focus on refrigerators, but the approach also applies to other major appliances. Our work is not complete but it is sufficiently advanced to demonstrate its merits *and* weaknesses. We hope that this description will stimulate recognition of the problem as well suggestions for improvements.

ELEMENTS OF THE NEW ENERGY TEST PROCEDURE

The actual test procedure consists of "hardware tests" and "software tests." The results of these tests are inputs to a model that simulates the appliance's energy use. The simulation model is programmed to predict energy use in any conditions requested by the user. The test conditions may be those specified by any of the major existing test procedures (ISO, DOE or

JIS). This predicted energy use is the information needed to demonstrate compliance with energy efficiency regulations or to prepare an energy label. Figure 1 shows the flow of information in the proposed test procedure. Each of these elements is described in detail in the following sections.

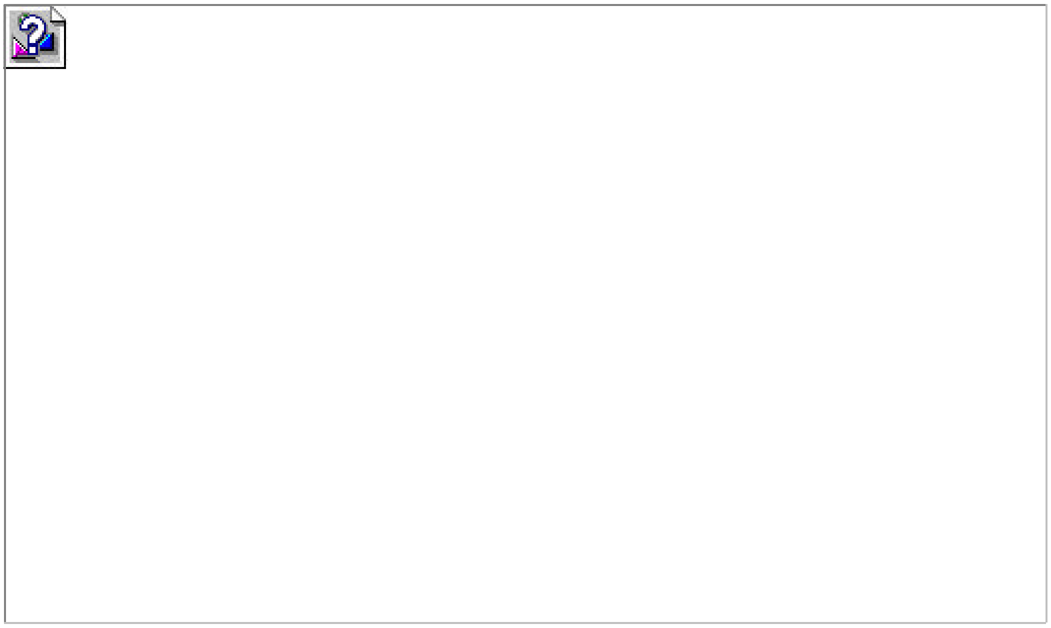

Figure 1. Elements of the new test procedure

HARDWARE TESTS

The goal of the hardware tests is to collect overall mechanical efficiency parameters for the appliance. An example of the kind of efficiency parameters collected in the hardware tests for a refrigerator is shown in Figure 2. Four separate hardware tests are performed. The shell test seeks to measure the overall heat loss coefficient of the refrigerator's box. The door test measures the heat gain caused by door openings (and thus captures certain aspects of the refrigerator's geometry). The COP test measures the efficiency of heat extraction over a range of temperatures. Finally, the load test captures the refrigerator's response to internal sensible and latent loads. These parameters are entered in the simulation model to help predict energy consumption of the refrigerator.

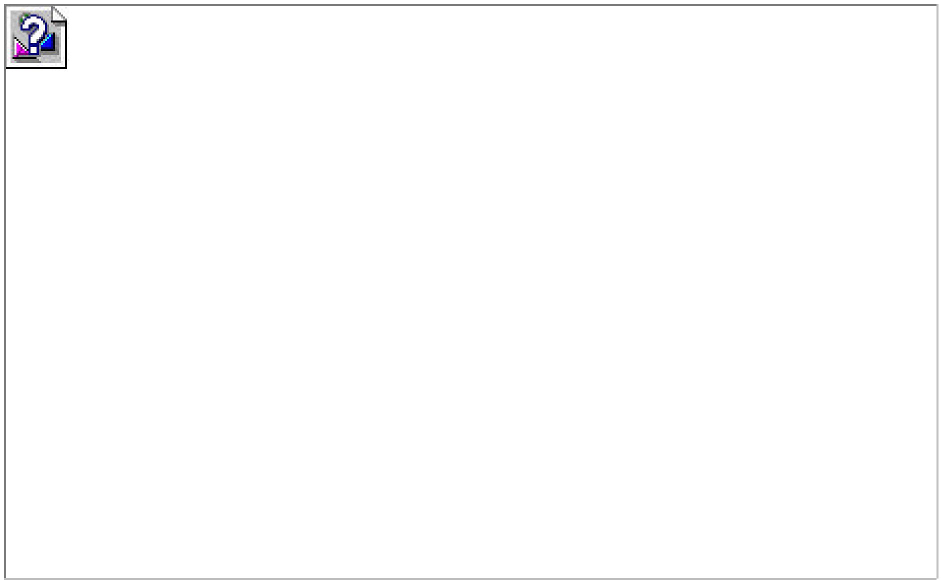

Figure 2. Hardware tests for the refrigerator

The hardware tests need to satisfy two conflicting requirements. The simulation model needs as detailed data as possible in order to be properly calibrated. On the other hand, we recognize that hardware tests are expensive and have limited precision. The challenge is to devise hardware tests that are simple to perform but yield sufficient information to accurately model the appliance's performance over a wide range of conditions.

The hardware test proposed to measure the refrigerator's efficiency of heat extraction (COP test) illustrates our attempts to satisfy the need for simple tests and performance data over a wide range of conditions. The goal is to measure the COP from part-load to full-load and at different ambient temperatures. In addition, the test must recognize that future compressors are likely to operate at different speeds or capacities. The test requires the placement of a remotely-controllable heater inside the refrigerator. The test consists of the following steps:

1. Place the refrigerator in a test chamber at a specified ambient temperature and lower the inside temperature until the compressor must cycle to maintain the desired temperature.
2. The test begins when the compressor on-time is much less than the compressor off-time.
3. The heater is switched on at low power, and the refrigerator's temperature is allowed to stabilize at the original temperature.
4. The power of the heater is increased in small steps, each time waiting for temperature stabilization to be achieved. Intervals between cycling become gradually shorter.
5. The power is increased until the compressor is no longer able to maintain the desired inside temperature–even when the compressor is operating constantly–and the inside temperature begins to rise.
6. Repeat steps 1–5 at a second ambient temperature.

The results of one series of tests are illustrated in Figure 3. The left chart shows the incremental increases in heater power over time.

Figure 3. Results of the COP test

The right chart shows the internal temperature at each level of heat input. The temperature fluctuates a little after each increase, but then returns to the thermostat setting. When the compressor's heat removal capacity is finally overwhelmed, the inside temperature climbs above the thermostat setting.

These measurements are sufficient to develop a performance curve (as shown in Figure 4) for the compressor system.

Figure 4. Performance curves for the compressor system

The surface captures efficiency at both part-load conditions and at two ambient temperatures. Interpolation to other temperatures is also possible without significant loss of accuracy. These performance curves will be used by the simulation model to predict energy consumption of the tested unit under nearly any desired condition.

We have developed hardware tests for measuring heat loss, door-opening, and loads, but there is not enough space here to describe them. These hardware tests are described in another document. [3] They differ from current energy tests because our goal is to extract performance parameters rather than energy consumption. Most of the tests could be easily automated, so they need not necessarily be more complicated to perform.

SOFTWARE TESTS

The goal of the software test is to evaluate the "intelligence" of the microprocessor. How does it respond to different situations? Are its algorithms crude or sophisticated? Are there certain combinations of conditions where the appliance behaves erratically? Are the algorithms consistent with the appliance's mechanical parameters?

We assume that the microprocessor can be interrogated, either in place via a communications cable, or extracted and tested on the bench. Even though this feature is not now generally available, we feel that this is a reasonable assumption for the future because manufacturers will want to interrogate the microprocessor in order to diagnose technical problems. Microprocessors can already be removed in most cars and some dishwashers (because manufacturers expect to change the cleaning algorithms when new detergents are introduced). Manufacturers are also creating prototype, "network ready" appliances.

Our approach to assessing the appliance's microprocessor relies on a form of reverse engineering. A computer creates thousands of different combinations of conditions. It submits them to the appliance microprocessor (as if these were the inputs from the controls and sensors) and records the microprocessor's responses. The computer assembles the microprocessor's replies into "response surfaces." An example of a 2-dimensional hypothetical response surface is shown in Figure 5.

Figure 5. A 2-dimensional response curve based on interrogations of the microprocessor

The response surfaces are converted into equations and passed to the simulation model. These equations will be used to control the appliance's operation.

Response surfaces may be relatively simple for most of today's appliances because the microprocessor typically controls one or two aspects of the appliance. For example, microprocessors in many refrigerators control the defrost interval and data displayed on a small screen. Future response surfaces will become very complex when the microprocessor controls several functions (such as defrost interval, compressor speed, and temperature distribution in a refrigerator) and relies on more than a few sensors. Microprocessors employing fuzzy logic, where their response depends on earlier conditions, add yet another layer of complexity. We anticipate that the microprocessor will need to be interrogated millions of times in order to develop smooth response surfaces. This can nevertheless be accomplished in a reasonably short time.

THE SIMULATION MODEL

The third element in the test procedure is a dynamic simulation model of the appliance. This model simulates the operation of the appliance and predicts its energy consumption under specified conditions. The specified conditions may be those specified by the ISO, DOE, or JIS tests or any other conditions.

Simulation models for several appliances have already been developed for refrigerators, air conditioners, furnaces, and water heaters. [4] Most of these models assume steady-state behavior; these are not realistic when trying to simulate the decisions of the microprocessor, which are dynamic. Recently, two water heater models [5] have been developed that simulate dynamic aspects, such as hot water draw-downs, the recovery period, and thermal stratification. These models resemble those used to simulate building energy loads, in which the materials, their physical properties, and geometry are all specified.

We also use a dynamic model, but employ a different approach for specification of the appliance. Our model relies on lumped parameters instead of detailed specifications of all of the physical characteristics of the materials and components. The model is very general and relies on inputs from the hardware and software tests to give it structure and uniqueness. Complex, dynamic models are now reasonably easy to construct using commercially available software, so models for other appliances could be made.

The software and hardware tests must be carefully coordinated with the simulation model. The challenge is to develop hardware and software tests that provide suitable parameters for use by the simulation model. We found that for the refrigerator model the approach to simulation depended upon the kinds of data available from the hardware and software tests. Likewise, we revised the hardware tests several times in order to provide the most useful information to the model. In other words, an iterative approach is most successful.

OUTPUT

The model simulates the appliance's operation and estimates its energy consumption. The model requires a detailed description of the hypothetical schedule and conditions, that is, the period of measurement, the ambient temperature, inside temperatures, humidity, number of door openings, etc. For example, the DOE refrigerator test specifies that the refrigerator be tested at ambient temperature of 32 °C for 24 hours, or from defrost to defrost. The JIS refrigerator test includes door openings with a specific schedule.

We successfully simulated the energy use of the same refrigerator when tested according to the ISO, DOE, and JIS test conditions. Thus, we were able to prepare energy consumption estimates (such as those needed for energy labels or regulatory purposes) for three different markets using a single test procedure.

CONCLUSIONS

We have presented a framework for a new energy test procedure. It addresses a major flaw in current test procedures, that is, they test only the mechanical aspects of the appliances and ignore software aspects. Microprocessor control (coupled to extensive use of sensors) is likely to save significantly more energy than mechanical improvements in the next decade, so it is important to capture those benefits.

Our approach also offers a novel solution to the harmonization problem. In the case of our approach, everyone can agree on the same hardware tests, software tests, and simulation model. Each country may select its own output from the model. This output (which might appear on its energy-use labels, or be part of its minimum efficiency regulations) would reflect the unique conditions faced there.

Our approach is considerably more complicated than current test procedures. This is not surprising, because it seeks to capture the energy impacts of complex interactions between mechanical and controls aspects of the appliance. Furthermore, we have not demonstrated that the hardware and software tests for one appliance are technically feasible and that a model can simulate all the key aspects of operation. Nevertheless, we have shown how the parts fit together and we have shown potential benefits from the proposed test procedure. We hope to refine the test and apply it to a real refrigerator soon. In the meantime, we invite your comments and suggestions.

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