Thermodynamics of Coffee Makers

By: Anthony J. Marchese, Shreekanth Mandayam and John L. Schmalzel
College of Engineering
Rowan University

Purpose:

Define and *measure* the thermodynamic efficiency of a coffee maker.

Calculate the energy losses that occur during the brewing and heating cycles.

Estimate the amount of power consumed annually in the United States from brewing coffee.

Student Groups:

Multidisciplinary groups of freshmen engineering students.

Equipment:

The apparatus consists of a Betty Crocker Series II 12 Cup Automatic Drip Coffee Maker (Model BC-1740) instrumented with 16 thermocouples, 1 digital watt meter and 1 flow meter. Type K thermocouples are used to measure the temperature at 16 different locations within the machine. A WD-768 Digital Watt Meter, which simultaneously measures power [W], current [A] and voltage [V], is used to monitor the instantaneous energy consumption. The flow rate is measured using an Omega FTB600 ultra-low flow sensor. Data is acquired using an Agilent3497A in conjunction with a Dell Optiplex GM+ 5133 PC. An AgilentE3613A power supply is used to provide excitation voltage to the flow meter.

Thermodynamic Efficiency:

The thermodynamic efficiency of a device is always defined as a ratio of the desired useful energy ("energy sought") divided by the energy that actually costs money ("energy bought"). For example, when you buy an air conditioner, it comes with a performance rating called the EER, which stands for Energy Efficiency Ratio. This value is merely the amount of heat that can be removed from your house in BTU/hr, divided by the electrical power requirements of the air conditioner in Watts:

$$EER = \frac{\text{Energy Sought}}{\text{EnergyBought}} = \frac{\dot{Q}[BTU/hr]}{\dot{W}[Watts]} .$$

How Do You Define Thermodynamic Efficiency for a Coffee Maker?

Energy Sought

In order to define the thermodynamic efficiency for a coffee maker (or any other household appliance), the "energy sought" must first be determined. The question here is: "What IS the desired useful energy?" Although water must be heated to the boiling point to pump the water out of the reservoir and to maximize the effectiveness of the leaching process in the filter basket, the actual desired result of the coffee maker is to produce coffee that is ready to drink. Therefore the desired useful energy corresponds to the net change in thermal energy of the water as it travels from the reservoir to the outlet of the filter basket.

Energy Bought

The energy that actually costs the consumer money is easy to determine in this case. A typical automatic drip coffee maker (and most other household appliances) requires electrical AC power, which costs the typical consumer anywhere from 0.08 to 0.15 $/kW-hr.

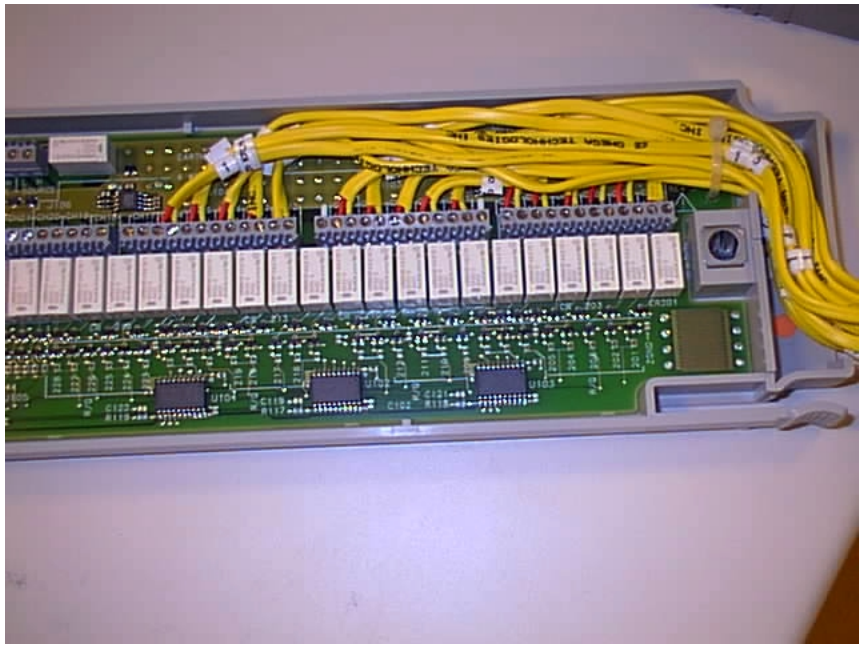
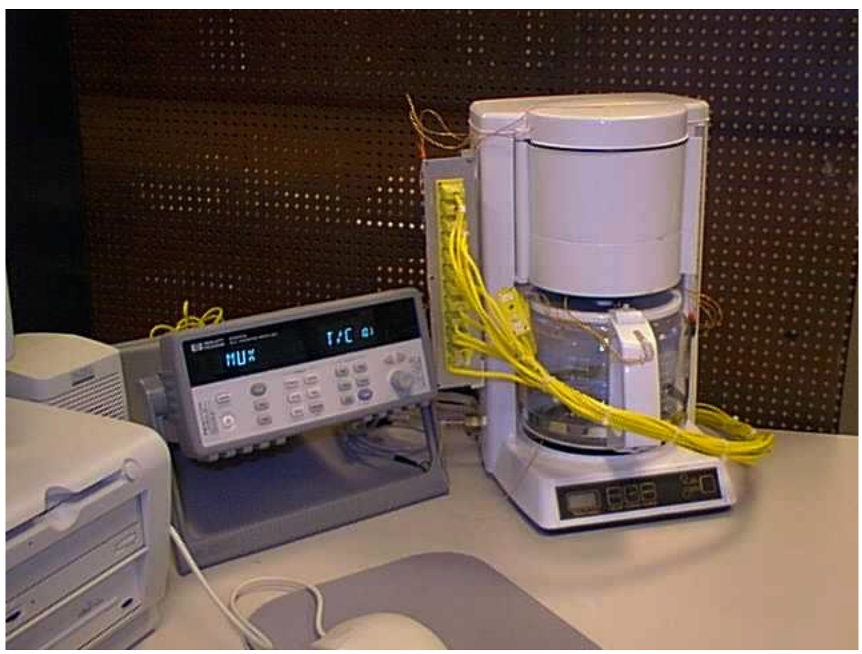


Figure 1. Coffee maker in test configuration.



The apparatus described above is now operated during the 10 minute brewing cycle, followed by approximately 30 minutes of the heating cycle, during which the heater turns on and off to maintain temperature in the carafe. During this period, data is acquired at 1 Hz and reduced as follows. During the brewing cycle, the net rate of heat addition to the water [W] as it flows from the heater inlet to the outlet of the filter basket is calculated from the following equation:

$$\dot{Q}_{17} = \dot{m} C_p (T_7 - T_1)$$

where $\dot{m}$ is the mass flow rate in kg/s, C_p is the specific heat of water in J/kg-K, T7 the filter basket outlet temperature and T_1 the water reservoir temperature in K. As described above, $\dot{Q}_{17}$ represents the "useful" portion of the energy consumption, since the overall goal of the device is to produce hot coffee. Since the instantaneous electrical power input to the machine, $\dot{W}$, is also measured, it is possible to calculate the instantaneous thermodynamic efficiency of the machine during the brewing cycle from the following equation:

$$\eta = \frac{\dot{m}C_p(T_7 - T_1)}{\dot{W}}.$$

Figure 2 is a plot of the instantaneous power consumption during the brewing and heating cycles and the instantaneous thermodynamic efficiency during the brewing cycle.

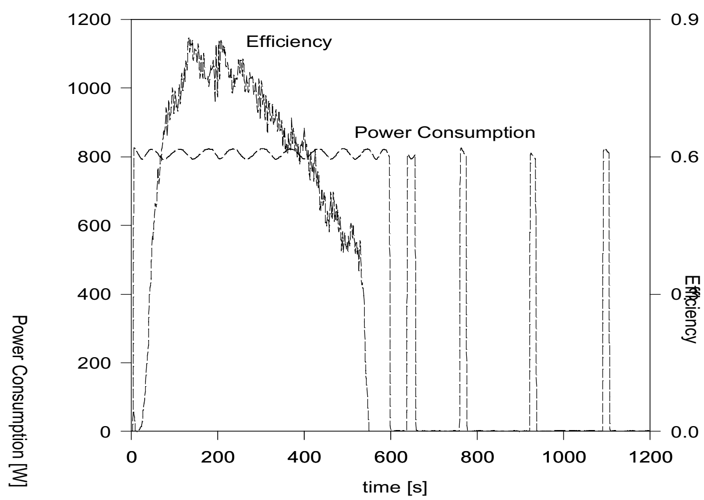


Figure 2. Instantaneous power consumption and energy efficiency for a typical coffee maker.

Additional Topics to Consider:

Where is the rest of the energy going?

Instead of being transferred to the water, some of the energy from the resistance heater is lost to the surroundings via heat transfer. By instrumenting the coffee maker with surface mount thermocouples on the inner and out surfaces at various locations, it is possible to calculate the instantaneous rate of heat loss in Watts. For example, the heat loss out of the top of the machine can be estimated from the following equation:

$$\dot{Q}_{top} = \frac{k_{pp}A_{top}\left(T_9 - T_8\right)}{t_{top}}$$

where k_{pp} is the thermal conductivity of the coffee maker shell (typically polypropylene) in W/m-K, Atop the area of the top of the coffee maker in m^2, ttop the thickness of the shell, T_9 the temperature of the inner surface of the shell in K and T_8 the temperature of the outer surface of the shell in K. Similar calculations can be repeated for various locations of the coffee maker body.

In addition to heat being lost to the surroundings, much of the energy from the resistance heater goes into heating up the structure of the coffee maker from room temperature to some elevated temperature. This mode of energy loss can also be estimated from the measured temperatures:

$$\dot{E} = \frac{d}{dt}(m_{cm}C_{v,cm}T) \approx \frac{m_{cm}C_{v,cm}}{2}\frac{d}{dt}(T_9 + T_8)$$

Where m_{cm} is the mass of the coffee maker structure, C_v the specific heat of the structure.

What is the annual U.S. coffee brewing energy consumption?

Finally, it is also possible to calculate the energy used during the entire process and to estimate the amount of energy consumed (and associated consumer cost) in the United States each year to brew coffee using residential coffee makers. To determine energy consumed per each brewing/heating cycle, it is necessary to integrate the power vs. time curve:

$$E = \int \dot{W} dt$$

where E is the energy in Joules. The integral is accomplished numerically using trapezoidal integration. To estimate the total U.S. annual energy consumption, convert from Joules to kW-hr and estimate the total number of brewing/heating cycles performed per year. An educated guess at this value is 30,000,000,000 brewing/heating cycles per year, resulting in 4,000,000,000 kW-hr per year, with an energy cost of $400 million dollars per year!