AME20213

James Joule's Mechanical Equivalent of Heat Experiment

1. Equipment

- Full-scale replica of Joule's experimental apparatus
- Two Type K thermocouples with digital temperature indicator
- Thermistor (Omega Model No. 44033)
- Drop weights (No. 808: 31.467 lbf [139.972 N], No. 809: 31.847 lbf [141.662 N])

2. Objective

Quantify the conversion of mechanical energy to heat energy by

(a) determining through measurement the mechanical energy expended,

(b) determining through measurement the heat energy gained,

(c) comparing the experimental results to those predicted by a model of the experiment, and

(d) identifying and quantifying any possible energy losses in the experiment.

3. Introduction

In 1850, James Prescott Joule reported to the Royal Society of London the results of a series of experiments in which he determined “the mechanical equivalent of heat with exactness”. His experiments truly accomplished the objective. His results established that “the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of force expended”, and that “the quantity of heat capable of increasing the temperature of a pound of water (weighed in *vacuo*, and taken at between 55 degrees and 60 degrees) by 1 degree Fahrenheit, requires for its evolution the expenditure of a mechanical force represented by the fall of 772 pounds through the space of one foot.”

Joule conducted five series of experiments using water, mercury, and cast iron. His experiments using water involved over one thousand trials, with each trial lasting almost an hour. Joule's use of the term *exactness* was not an exaggeration. Joule carefully designed his experiment to minimize any energy losses, such as friction and heat transfer to the environment.

Even so, some losses occurred. He extensively considered and quantified all possible losses, such as the energy loss resulting from slightly stretching the string that held weights as they fell.

Today, the amount of energy required to raise a mass of water by a certain temperature is determined using the specific heat at constant pressure of water, which is 4186 J/(kg K). Thus, 4186 J or 4.186 kJ are required to raise 1 kg of water by 1 K. In the English Engineering system of units, this energy is 778 ft lbf. Joule's number (772 ft lbf) differs from the present value by less than 0.8 %.

4. Experimental Apparatus

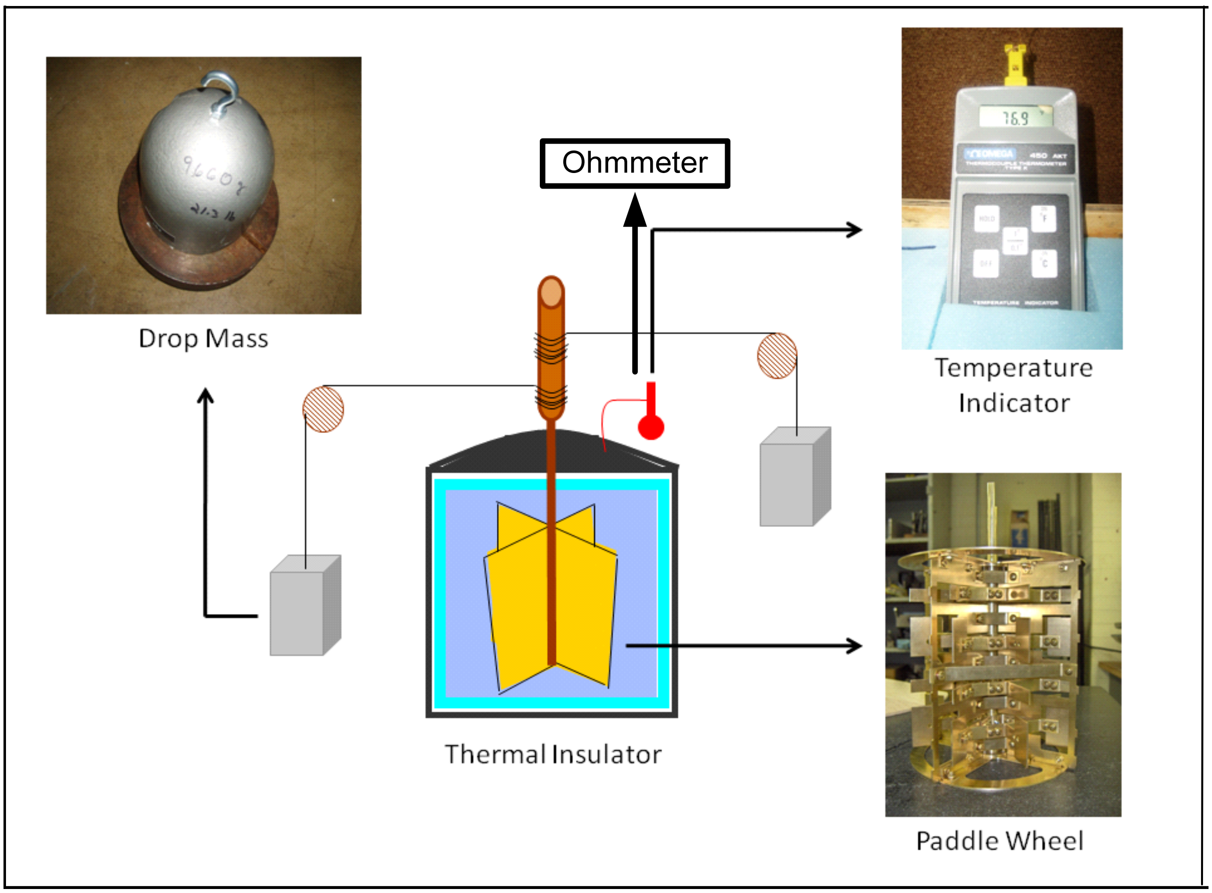

Figure 1. Overview of the Joule apparatus

The main component of this experiment is the Joule apparatus. The apparatus basically works as follows. A weight connected to a pulley system is dropped from a known height, thereby turning side pulleys in the system. A center pulley in turn rotates a paddle wheel inside a container containing liquid. The outside of the container is thermally insulated to prevent heat loss from the container. Rotating the paddle wheel causes the temperature of the liquid to rise. A schematic of the experimental apparatus is shown in Figure 1.

The paddle wheel with its many fins is fitted inside the thermally insulated container. A thermocouple and a thermistor are mounted at the same location inside the container such that they are exposed directly to the liquid filling the container. The thermocouple wire is extended to a digital thermocouple indicator that is located outside the container's insulation; the thermistor wire to a digital ohmmeter to measure its resistance. The shaft of the paddle wheel is connected through wires to a center pulley located directly above the paddle wheel and then to two side pulleys, one on each side of the support structure. A weight can be attached to the end of each wire using a hook. The experiment is performed by attaching a known weight to one wire, dropping it a known distance, and then removing the weight. During this event, the wire on the other side is wound up. The experiment continues by attaching another weight and then dropping the weight as before. This process is repeated many times such that a measurable increase in the liquid's temperature is observed.

5. Analysis

In Joule's apparatus, the gain in the paddle wheel's energy from the energy gained in dropping the weight becomes the gain in the heat energy of the liquid. The potential energy loss (or “force expended” in Joule’s words) per weight drop equals $w\Delta h$, where w is the weight and Δh is the height over which the weight is dropped. This loss becomes the gain in the paddle's mechanical energy, ΔE_m. This mechanical energy is delivered to the liquid by the fins of the turning paddle wheel's fins, causing an increase in the liquid's thermal energy, ΔE_t (the “quantity of heat produced” in Joule’s words). This thermal energy gain is expressed as $m_L C_p \Delta T$, where m_L is the mass of the liquid, C_p its specific heat at constant pressure of the l;iquid, and ΔT the increase in temperature of the liquid. The mass of the water can be determined from its density, ρ, and its known volume, V_l, using the expression $m = \rho V_l$.

6. Procedure

Before beginning, assign tasks among your group. Have one person be responsible for recording the temperature, time, and data. Have each of the other two responsible for dropping a weight on a side of the apparatus. Table 3 is provided at the end of this document for your convenience to check each time that a weight is dropped. This helps because after the 77th weight drop you may not remember if it was the 77th drop or the 78th drop.

1. Measure the distance that a weight drops. Record the distance in Table 1.
2. Record the ambient temperature, the thermistor resistance, and the time at which you begin the experiment in Table 2.
3. Secure one of the weights to the wire on one side of the apparatus. Let the weight drop and record the amount of time it takes to drop using the stopwatch. The amount is approximately 25 seconds. Record the time in Table 1.
4. Remove the weight from the wire.
5. Secure the other weight to the wire on the other side of the experiment. Let the weight drop.
6. Remove the weight from the wire.
7. Repeat steps 3 through 6 four more times, but do *not* measure the time for the weight to drop anymore. This will amount to a total of 10 weight drops, 5 for each side.
8. Record the time, thermistor resistance, and temperature of the liquid using the digital thermometer. The temperature change for this number of weight drops will be small, possibly only 0.1 °F to 0.2. °F. Do not be discouraged! Joule was not. He persisted.
9. Repeat steps 3 through 8 nine more times, for a total of 100 weight drops. Be sure to record the final temperature, thermistor resistance, and time. If you have more time, continue repeating the weight drops to achieve a greater temperature rise. Finally, be sure record any other information that you think you may need to analyze the results.

Notes:

- One hundred weight drops should take approximately 45 minutes.
- A temperature increase of greater than approximately 1 °F should occur for water.

Distance for first weight drop (cm)	
Time for first weight to drop (s)	

Table 1. Weight drop distance and time.

Number of Drops	**Time**	**Temperature (°F)**	**Resistance (kΩ)**
0			
10			
20			
30			
40			
50			
60			
70			
80			
90			
100			

Table 2. Drop-time-temperature-resistance data.

Drop Number	1	2	3	4	5
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Table 3. To be used for marking each time that a weight is dropped.

Supplemental Information

1. Liquid Container:

Material: Brass

Mass: 1.378 kg

Volume of distilled water in container: 5830 mL

2. Paddle Assembly:

This consists of a rotating paddle and a stationary frame. The paddle assembly is housed inside the liquid container. A shaft connects the rotating paddle to the center pulley located directly above the paddle assembly. For moment-of-inertial considerations, treat the rotating paddle as a plate that rotates about its end.

Rotating Paddle and Stationary Frame Material: Brass

Rotating Paddle Mass: 1.200 kg

Stationary Frame Mass: 2.037 kg

Rotating Paddle Radius: 6 in.

Shaft Radius: 0.5 in.

3. Center Pulley:

This is located directly above the paddle assembly and is connected with string to two larger side pulleys, one on each side of the apparatus. For moment-of-inertial considerations, treat the center pulley as a cylinder that rotates about its longitudinal axis.

Material: Phenolic

Center Pulley Radius: 2 in.

Center Pulley Length: 8 in.

4. Side Pulley:

There are *two* side pulleys. *Each* side pulley consists of a larger wood pulley that is connected rigidly to *two* aluminum pulleys, one on each side of the wood pulley. For moment-of-inertial considerations, treat each pulley as a cylinder that rotates about its longitudinal axis.

Wood Pulley Material: Pine

Wood Pulley Radius: 6 in.

Wood Pulley Thickness: 2.25 in.

Al Pulley Radius: 1 in.

Al Pulley Thickness: 4.5 in.