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The effect of friction on heat generation between surfaces

Tanay Nistala
nistalatanay@gmail.com
Dhirubhai Ambani International School, Mumbai, Maharashtra

ABSTRACT

Friction is present in every aspect of the world where two objects move past each other. In some cases, they are useful and almost indispensable, like helping us walk, or letting cars slow down. In others, they are a nuisance, especially in motors and other mechanical application which try to reduce friction as much as possible. However, it is an essential phenomenon to consider, especially in the design and construction of heavy machinery, cars, airplanes, and even robots. Heat has also been important to mankind since the beginning. It helps us keep warm and cook food. In this paper, I aim to test the effect of friction on heat generation between two surfaces. Research Question: How do the materials or surfaces involved in friction affect the heat generation due to friction from a grinder with surface velocity 26.3 ms^{-1} and an external force of 0.37N?

Keywords— *Friction, Heat*

1. INTRODUCTION

Friction is present in every aspect of the world where two objects move past each other. In some cases, they are useful and almost indispensable, like helping us walk, or letting cars slow down. In others, they are a nuisance, especially in motors and other mechanical application which try to reduce friction as much as possible. However, it enables life as we know it, and especially in physics, it is an essential phenomenon to consider, especially in the design and construction of heavy machinery, cars, airplanes, and even robots. Heat has also been important to mankind since the beginning. It helps us keep warm and cook food.

One of the most well-known aspects of friction is the heat generation caused by it. It's why rubbing your hands in the cold makes you feel warmer, and why spaceships burn up on re-entry. The link between friction and its heat generation has also enabled innovation in various fields, as man has tried to reduce this effect as much as possible to make the most efficient systems.

The former of the above is one reason I chose this topic, as at a young age it has always been fascinating to me how rubbing your hands together for just a few seconds can make you feel so much warmer. Secondly, I am involved in robotics, where we employ bushing surfaces and bearings heavily to reduce friction between surfaces and shafts in order to increase efficiency.

Hence, I aimed to test the effect of friction on heat generation between two surfaces.
Research Question: *How do the materials or surfaces involved in friction affect the heat generation due to friction from a grinder with surface velocity 26.3 ms^{-1} and an external force of 0.37N?*

2. BACKGROUND INFORMATION

This experiment deals with friction and its effect on heat generation when two objects slide or rub against each other. Thus, it will focus and analyze dynamic friction. Friction is essentially a force that opposes motion. In particular, dynamic friction, the kind of friction being studied, is "a force opposing motion when a body moves".

This arises due to differences in the shapes of the surfaces in contact at a microscopic and even atomic level:

As the friction causes a change in the motion of an object, usually slowing it down, it does work on said object, causing an increase in its energy. Some of this energy results in an increase in temperature, which is what will be studied. This temperature change depends on the specific heat capacity (c) of the object, which can be related to the energy change as follows:

$$\Delta E = mc\Delta T$$

Where ΔE is the energy change, m is the mass of the object, c is the specific heat capacity, and ΔT is the change in temperature of the object.

The energy change of the object itself can be calculated using the following equation:

$$\Delta E = Fs\cos\theta$$

Where ΔE is the energy change, F is the force applied on the object, s is the distance the force was applied over, and θ is the angle between the direction of application of the force and the direction of the object's motion.

The force itself can be found by the following equation, where μ_d is the coefficient of dynamic friction and N is the normal force between the two surfaces:

$$F_{fric} = \mu_d N$$

Thus, we can combine these equations to get the following:

$$\Delta E = F_{fric} s\cos 0°$$
$$\Rightarrow \Delta E = \mu_d N s$$

We can then calculate the distance over which the force was applied by multiplying the surface speed, v, with the time of contact, t:

$$\Rightarrow \Delta E = \mu_d N v t$$

However, it soon became evident that the temperature change would depend largely on the specific heat capacity of the substance, with a smaller dependency on the frictional force; in effect, what would need to be studied is the difference between the energy supplied ($\Delta E = F_{fric} s\cos\theta$) and the energy converted to heat ($\Delta E = mc\Delta T$).

Thus, by the following equation the efficiency of frictional heat generation (eff) can be found:

$$eff = \frac{mc\Delta T}{\mu_d N v t}$$

Based on this equation, it can be hypothesized that *the efficiency of heat generation between two surfaces is directly proportional to the ratios between their specific heat capacities and coefficient of dynamic friction.*

3. METHODOLOGY

In this experiment, the friction was provided by a Bosch GBG 35-15 bench grinder, with a 60 grit grinding wheel. This grinding wheel is coated in polycrystalline aluminum oxide (Al_2O_3), along with small quantities of other abrasives, although only the aluminum oxide will be considered for this experiment. This coating results in a relatively high friction coefficient and therefore results in higher friction and heat generation. Although the use of a grinder reduces uncertainties as it is designed to grind down other objects without wearing out itself, it does reduce the mass of the objects used slightly, albeit by a negligible amount.

The materials used were 304 alloy stainless steel, 6061 aluminum alloy, acrylic (Plexiglas), and 60 grit sandpaper (coated in corundum/Al_2O_3). The following table shows some data for each of these surfaces:

Material Characteristics

Surface	Mass / g	Specific Heat Capacity / kJ kg^{-1} K^{-1}	Coefficient of Friction (with aluminum oxide)
Stainless Steel	5.19	0.460	1.1
Aluminum	4.96	0.904	1.36
Acrylic	12.46	1.470	0.27
Sandpaper	5.45	1.400	0.85

3.1 Variables
Independent Variable: Surface material
Dependent Variable: Temperature change

Control Variables

Control Variable	Reason for Controlling	How it was Controlled
External force applied	The force applied affects the friction between the surfaces and thus the heat generated	Force exerted by hand was kept roughly constant as the same person applied the force using muscle memory
Surrounding room temperature	The surrounding room temperature affects how quickly the object loses heat during the heating	Trials were conducted in the same room at the same time
Time of contact	Affects how much each substance heats, and how much heat is conducted away from point of contact	Time was fixed to be ~15 seconds, measured with a stopwatch
Grinder surface material	Only one material should be changing between friction surfaces	Same grinder was used throughout, with a 60 grit polycrystalline aluminum oxide coated grinding wheel
Speed of grinder/moving surface	Relative speed of the surfaces affects the heat generated	The grinder ran at the same speed setting throughout.

3.2 Apparatus
- Assortment of Surfaces
  - Stainless Steel (304 alloy)
  - Aluminum (6061 alloy)
  - Acrylic (Plexiglas)
  - Sandpaper (60 grit corundum)
- Thermocouple Thermometer
- Bench Grinder
- Weighing scale
- Stopwatch
- Gloves
- Goggles

3.3 Procedure
(a) Record mass of sandpaper
(b) Record initial surface temperature of sandpaper
(c) Hold sandpaper against grinder for 15 seconds with constant force
(d) Record final surface temperature of sandpaper
(e) Repeat steps 1 to 4 for aluminum, stainless steel, and acrylic

3.4 Risk Assessment
Care had to be taken to ensure safety during this experiment, as it depended on a bench grinder that ran at over 3000 rpm, which is dangerous if touched, especially due to its rough surface. Furthermore, it gives out sparks on contact with stainless steel, and small pieces and dust of the materials in contact with it may go flying, while the material itself became very warm. Due to this, precautions taken involved wearing safety goggles to shield the eyes, and gloves to protect one's hand from the heat. Moreover, ear muffs were worn due to the large amount of noise produced by the grinder.

4. DATA COLLECTION AND ANALYSIS
4.1 Observations
Although forces cannot be seen, its effects are visible. During the experiment, it was noticed that the materials being used, especially the metal ones, quickly became warm to the touch, suggesting that heat is generated. However, in some trials the heat became unbearable to hold while in others it didn't. Furthermore, each material behaved differently with the grinder itself; stainless steel and aluminum warmed and were smoothened, acrylic sheared at the contact point, and no visible difference was seen on sandpaper.

4.2 Raw Data
Force applied: 0.37N
Surface Speed: 26.3 ms^{-1}

Raw Data

Surface	Mass / g	Trial 1			Trial 2			Trial 3		
		T_{init} / °C	T_{final} / °C	t / s	T_{init} / °C	T_{final} / °C	t / s	T_{init} / °C	T_{final} / °C	t / s
Stainless Steel	5.19	24	145	15.23	26	140	14.88	24	82	14.87
Aluminum	4.96	23	63	15.40	29	89	14.91	25	72	15.55
Acrylic	12.46	23	32	14.87	25	29	14.97	25	35	15.09
Sandpaper	5.45	23	51	15.25	23	44	14.91	26	55	15.04

4.3 Data Processing and Error Propagation

The following table shows average values for the temperature change and time of contact measured for the experiment.

Averaged Data

Surface	Trial 1		Trial 2		Trial 3		Average	
	ΔT / °C	t / s	ΔT / °C	t / s	ΔT / °C	t / s	ΔT / °C	t / s
Stainless Steel	121	15.23	114	14.88	58	14.87	98	14.99
Aluminum	40	15.40	60	14.91	47	15.55	49	15.29
Acrylic	9	14.87	4	14.97	10	15.09	8	14.98
Sandpaper	28	15.25	21	14.91	29	15.04	26	15.07

There are several sources of error that were attempted to control, such as the force exerted on the surfaces, the mass of the objects used, and the time of contact. We can calculate the uncertainty in the time of contact for each material, and the mass of the objects to find the expected random error. The uncertainty in the contact time can be found using the minimum and maximum times taken for each material, while the uncertainty in the mass would be the uncertainty in the measuring instrument used.

$$\Delta t = \frac{t_{max} - t_{min}}{2}$$
$$\Delta m = \pm 0.01g$$
$$\Delta N = \pm 0.01N$$

Thus, we get the percentage uncertainty in efficiency, $\%eff$, to be:

$$\%eff = \%t + \%m + \%N$$

The following table lists the uncertainties Δt, Δm, and Δeff:

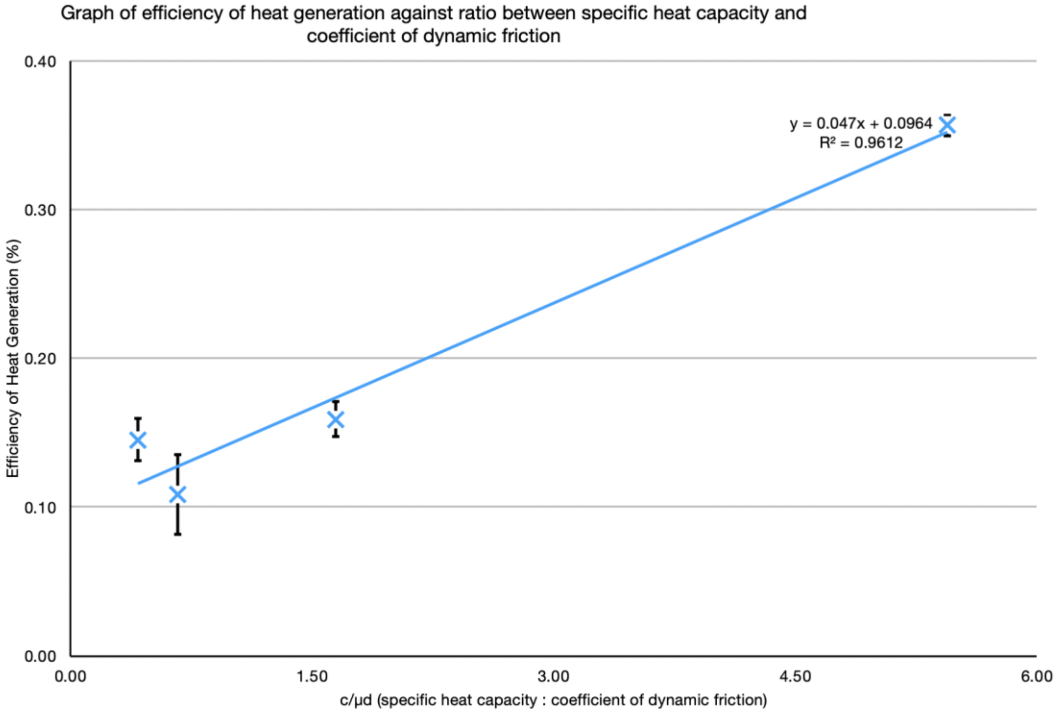
Errors

Surface	Mass / g (±0.01g)	Average		Efficiency / %	ΔEff
		t / s	Δt / s		
Stainless Steel	5.19	14.99	0.36	0.48	0.014
Aluminum	4.96	15.29	0.64	0.41	0.020
Acrylic	12.46	14.98	0.22	0.36	0.007
Sandpaper	5.45	15.07	0.34	0.41	0.012

Combined with the material data, we can calculate the change in heat energy as well as the total energy gain due to the friction, which in turn gives the efficiency of frictional heat generation for each material. Since this efficiency, in theory, depends on two separate properties of the materials, specific heat capacity and coefficient of friction, the efficiency will be compared with the constant $\frac{c}{\mu_d}$ specific to each material. The table and graph for this data are shown below:

Processed Data

Surface	Mass / g	Specific Heat Capacity / kJ kg⁻¹ K⁻¹	Coefficient of Friction	Average		Heat Energy / kJ	Total Energy / kJ	Efficiency / %	c/μ_d
				ΔT / °C	t / s				
Stainless Steel	5.19	0.460	1.1	98	14.99	0.23	160.49	0.15	0.42
Aluminum	4.96	0.904	1.36	49	15.29	0.22	202.31	0.11	0.66
Acrylic	12.46	1.470	0.27	8	14.98	0.14	39.35	0.36	5.44
Sandpaper	5.45	1.400	0.85	26	15.07	0.20	124.62	0.16	1.65



There is a clear linear trend shown between the ratio of specific heat capacity to coefficient of friction of a substance and the efficiency of the heat conversion. This suggests that as the specific heat capacity of a substance increases, the efficiency of frictional heat generation decreases, and vice versa. As for the coefficient of friction, as it increases the efficiency of frictional heat generation decreases, and vice versa.

This confirms the hypothesis that as the ratio between specific heat capacity and coefficient of friction increases, the efficiency of heat generation increases linearly. This also confirms the mathematical expression found, $eff = \frac{mc\Delta T}{\mu_d Nvt}$, as it suggests that the relation between them is directly proportional.

However, looking at the exact values of the trend we see that the equation $y = 0.047x + 0.0964$ suggests that for an object with a specific heat capacity of zero, the efficiency would be almost 9.6%, as compared to 0% theoretically. The R^2 value of 0.9612 suggests that the trend is relatively strong, which suggests that the error is systematic, and was likely overlooked in the experiment. This also shows us that the trend shown is not perfect and has a margin for error.

5. CONCLUSION

In conclusion, as the specific heat capacity of an object increases, and its coefficient of friction decreases, the efficiency of heat generation decreases; that is, the proportion of the energy converted to heat decreases. Without the influence of some hard-to-control factors, the efficiency of heat generation is directly proportional to the specific heat capacity of the objects in contact and inversely proportional to the coefficient of friction between the surfaces. This can be explained by the equation derived earlier. Thus as the ratio $\frac{c}{\mu_d}$ increases from around 0.5 to just under 5.5, the efficiency increases from 0.11% to 0.36%. With an error margin up to 4.8%, and an R^2 value of 0.96 it can be concluded that the results achieved are relatively reliable and accurate, although there are some other factors that could affect it. Overall, this experiment is a success as the hypothesis was proved, and some additional factors were identified to be affecting the efficiency of heat generation.

6. EVALUATION

Although the hypothesis was somewhat proved and the experiment was a success, there were some issues. Firstly, the results obtained did not signify an exact direct proportion relation, as suggested by the equation. Furthermore, there were some sources of error that were hard to control, such as the force applied by hand on the object in contact with the grinder. This uneven force would have affected the readings.

The other issue had to do with the objects used. As only part of the surface was used for friction, heat was generated over a small surface area and then dissipated to the other parts of the object. In the metallic objects, this heat distribution was relatively uniform, but in the sandpaper and the acrylic, with lower thermal conductivity, the heat did not spread to through the entire object and so the calculation of heat energy as $E = mc\Delta T$ would have been inaccurate as the whole object did not change temperature by the same amount.

Another source of error involves the loss of mass of the objects used. The grinder shaved off the surfaces of each object slightly, resulting in the mass of the objects slowly dropping. However, this change in mass was very small (<< 0.01g) and so its effect could be negligible.

Moreover, the objects used were likely not pure. The metals used were alloys that had some margin of error in their contents, and the sandpaper used had a corundum surface, which is comprised of several different minerals. This meant that the specific heat capacity used was not entirely accurate for these. However, in spite of these shortcomings, the experiment's results signify a success in achieving the aim of the experiment.

In the future, it is recommended that the experiment be carried out with a greater selection of materials with varying degrees of heat capacities and coefficients of friction, as well as controlling the force applied better to remove human error.

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