

Mechanical Equivalent of Heat

- **Related topics**

Mechanical equivalent of heat, mechanical work, thermal energy, thermal capacity, first law of thermodynamics, specific thermal capacity.

- **Principle**

In this experiment, a metal test body is rotated and heated by the friction due to a tensed band of synthetic material. The mechanical equivalent of heat is determined from the defined mechanical work and from the thermal energy increase deduced from the increase of temperature. Assuming the equivalence of mechanical work and heat, the specific thermal capacity of aluminum and brass is determined.

- **Equipment**

Mechanical equiv. of heat app.	1
Friction cylinder <i>CuZn</i> , $m = 1.28 \text{ kg}$	1
Friction cylinder <i>Al</i> , $m = 0.39 \text{ kg}$	1
Support rod -PASS-, square, $l = 250 \text{ mm}$	1
Right angle clamp -PASS-	1
Spring balance 10 N	1
Spring balance 100 N	1
Stopwatch, digital, $1/100 \text{ sec.}$	1
Bench clamp, -PASS-	1
Universal clamp with joint	1
Commercial weight, 1000 g	1
Commercial weight, 5000 g	1



Fig. 1: Experimental set-up: Mechanical equivalent of heat.

- **Tasks**

1. Determination of the mechanical equivalent of heat.
2. Determination of the specific thermal capacity of aluminum and brass.

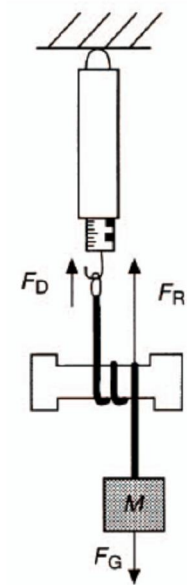


Fig. 2: Equilibrium of forces when the friction cylinder is rotated.

- **Set-up and procedure**

The experimental set-up is shown in *Fig. 1*. To start with, the friction cylinder and the crank handle are fixed to the rotating bearing and the base plate is clamped very firmly to the table with the screw clamps. Failure to do so may cause tilting of the base plate during cranking, which in turn may cause the thermometer introduced into the bore hole to break. The friction band fastened to the dynamometer is laid 2.5 times around the friction cylinder (so that the dynamometer is relieved when the crank is turned clockwise).

The 5 kg weight is attached to the lower end of the friction band. To measure temperature, the thermometer is held with a universal clamp and carefully introduced into the bore hole of the friction cylinder. The thermometer and the bore hole of the cylinder must be carefully aligned, so the thermometer will not break while the cylinder is rotating. To improve thermal contact, the borehole is filled with heat conducting paste.

In order to increase the temperature of the cylinder and determine the rate of heat loss towards the environment the crank handle is first turned for about 20 times. The

temperature is recorded *every thirty seconds* during four minutes. After this, the crank handle is turned a certain number of times (e.g. 200times) as fast and regularly as possible. Simultaneously, the force F_D acting on the suspension is determined with the dynamometer. Subsequently, the continuous temperature decrease is noted at intervals of *thirty seconds*.

The second part of the experiment is carried out similarly, in order to measure the thermal capacity of an aluminum cylinder and that of a brass cylinder whose mass is double the mass of the aluminum cylinder. Before starting the experiment, the friction cylinder and the friction band should be wiped with a dry cloth to rid them from metallic abrasion dust. When using the aluminum cylinder, friction should not exceed 10 N, (for this, the 1 kg weight and the more precise 10 N dynamometer are used), in order to avoid severe abrasion and soiling of the friction band. The specific thermal capacity of the cylinder is calculated from the number of crank rotations, the mean force at the dynamometer F_D and the increase of temperature T .

- **Theory**

For a long time it was debated as to whether the heat of a system, which used to be defined in terms of its temperature, was a form of energy or an independent magnitude which is conserved. During the first half of the nineteenth century, it was proven that mechanical energy due to friction is completely converted to heat, independently of the course of the transformation process and of the physical and chemical characteristics of the material used. Heat was accordingly defined as the energy of disorganized, macroscopically invisible molecular movements.

The quotient between realized mechanical work W and the quantity of heat Q generated through friction is called the mechanical equivalent of heat. In this experiment, mechanical work is performed by rotating the friction cylinder against the sliding frictional force F_R of the synthetic friction band. As weight M (cf. Fig. 2) is not accelerated when the crank is rotated, weight $F_G = Mg = 49 \text{ N}$ (M mass of the weight, g terrestrial gravitational acceleration) on one side and the sliding frictional force F_R acting together with force F_D on the suspension of the dynamometer on the other side, must cancel each other:

$$F_R = F_G - F_D \quad (1)$$

Friction work W is thus determined from the friction path of $2\pi r n$ (r = radius of the cylinder, n = number of turns) and is found to be:

$$W = 2\pi r n F_R = 2\pi r n (F_G - F_D). \quad (2)$$

Whilst the synthetic band slides over the cylinder, a large portion of mechanical work is converted to thermal energy Q through inelastic deformations of the friction material. Accordingly, the temperature T of the friction cylinder increases from T_1 to T_3 . Simultaneously, a certain amount of energy, Q_{loss} , is dissipated in the environment (atmosphere), due to radiating and convective losses:

$$Q = C_{tot} (T_3 - T_1) + Q_{loss}. \quad (3)$$

C_{tot} is the total thermal capacity of the heated parts. It is the sum of the thermal capacity C_{cyl} of the friction cylinder (mass m , specific thermal capacity c (CuZn: $c = 0.385$ J/(g·K)):

$$C_{cyl} = m c, \quad (4)$$

of the thermal capacity of the friction band ($C_{band} = 4$ J/K) and of the thermal capacity of the thermometer ($C_{th} = 4$ J/K). If the mass of the friction cylinder is $m = 640$ g, total thermal capacity amounts to:

$$C_{tot} = C_{cyl} + C_{band} + C_{th} = 254 \text{ J/K}. \quad (5)$$

The thermal capacities of the insulated bearing and of the heat conducting paste were neglected.

Figure 3 displays a temperature-time diagram for an example of measurement. During the crank turning maneuver, the temperature recording is not possible. The rotation of the crank handle stops at the moment corresponding to the point 2. After that, the temperature is seen to further increase due to the limited rate of spread of the heat in the metal piece. A slight maximum in temperature (3) is attained and followed by the exponential decrease due to the loss of heat to the environment. The energy lost in the environment during the crank turning maneuver is not easy to measure. One would need

special calorimetric arrangements for minimizing these losses. Such high-standard devices are not available in the present set up, so one has to rely on other grounds to evaluate the losses. One idea would be that, during the heating process between the states 1 and 3, the rate of energy flow out of the system (that is the rate of decrease of the system's temperature) is almost the same as the one after the state 3 is reached (Fig. 3). Thus, by extending linearly the last part of the time-temperature diagram to the left of point 3, an intersection point 4 with the parallel to the ordinate axis passing through the state 1 would be obtained. One may thus assume that $T_4 - T_3$ would approximate the temperature variation of the system, due to environmental losses, if it would fictitiously receive instantly all the energy Q . Therefore, one may write $Q_{loss} = C_{tot} (T_4 - T_3)$ and Eq. (3) finally reads:

$$Q = C_{tot} (T_4 - T_1). \quad (6)$$

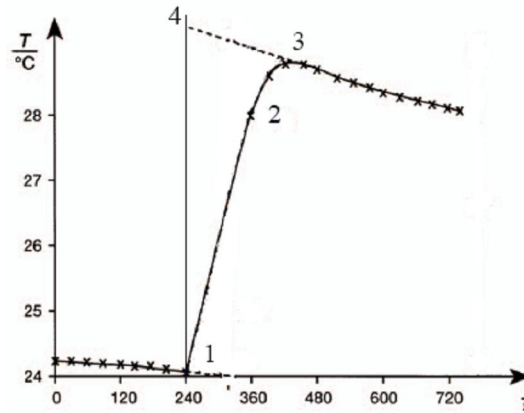


Fig.3: Temperature-time diagram for a measurement example

In the case of a measurement example where the residual load on the dynamometer is $F_D = 3$ N, work after 200 rotations of the friction cylinder amounts to:

$$W = 1301 \text{ J.}$$

According to equation (3), the resulting temperature increase of the friction cylinder, $\Delta T = 5.1$ K, produces the following amount of thermal energy:

$$Q = 1296 \text{ J.}$$

If the mechanical heat equivalent is calculated, the quotient (1.003) amounts to 1 within the limits of measurement error. As heat is a form of energy, the total amount of mechanical energy must be transformed into an equal amount of heat energy according to the law of conservation of energy. In fact, the mechanical equivalent of heat must thus amount to:

$$\frac{W}{Q} = 1. \quad (7)$$

Similar experiments, in which electric energy is converted to thermal energy, show that the corresponding electric equivalent of heat $\frac{W_{el}}{Q}$ also amounts to 1. These results are comprehensively summarized in the first law of thermodynamics.

The change of internal energy ΔU of a system is equal to the amount of heat energy Q and to the amount of work W supplied from outside, independently of the supply procedure:

$$\Delta U = Q + W. \quad (8)$$

If, inversely, equation 6 is assumed ($W = Q$), the specific thermal capacity can be determined with this equipment. If equations 3 and 5 are transformed according to the thermal capacity of the friction cylinder, the following result is obtained:

$$C = \frac{W}{\Delta T} - 8 \frac{J}{gK}, \quad (9)$$

where the last term represents the already mentioned contributions from the friction band and thermometer.

The specific thermal capacity, defined as the quotient between the thermal capacity of a body C and its mass m :

$$c = \frac{C}{m}, \quad (10)$$

is a material constant, which at normal ambient room temperatures and atmospheric pressure depends very little on absolute temperature. It is to be noted from equation 9 that the thermal capacity of a homogeneous material is strictly proportional to its mass.

An example measurement with a rest load $F = 4 \text{ N}$ on the dynamometer, 200 turns of the crank, and a temperature increase of $\Delta T = 2.5 \text{ K}$ yielded a thermal capacity of

$$C = 501 \text{ J/K},$$

for a brass cylinder of 1280 g. (that is actually about twice the thermal capacity of a cylinder of half the weight (247 J/gK)). The specific thermal capacity calculated with equation 9 is:

$$c_{\text{brass}} = 0.392 \text{ J/(g}\cdot\text{K)}.$$

The measurement of the aluminum cylinder yielded the following value:

$$c_{\text{Al}} = 0.870 \text{ J/(g}\cdot\text{K)},$$

as compared to the known value $c_{\text{al}} = 0.902 \text{ J/gK}$ for the specific thermal capacity of aluminum at room temperature.

- **Errors**

One of the major error sources of this experiment is the actual computation of the average ΔT from the graph. This method raises a systematic error that should be estimated.

Other accidental errors are caused by factors such as poor thermal contact, irregular turning of the handle, severe abrasion and soiling of the friction band. There are also other computational errors due to approximation or neglecting of certain values (thermal capacities of the insulating bearing and the heat conducting paste).