PHYSICS

THE EFFECT OF MATERIAL OF WIRE ON THE SPEED OF PASSING THROUGH A BLOCK OF ICE

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TIIVISTELMÄ

Tässä tutkielmassa tutkitaan metallilangan materiaalin vaikutusta aikaan, joka siltä menee läpäistä jääsauva. Tätä tutkittiin kokeellisesti huoneenlämmössä käyttäen lankoja, joiden halkaisija on 2 mm ja jotka ovat eri materiaaleja ja joihin on kiinnitetty 300 g paino. Tutkintalaitteisto koostui telineestä, johon oli asetettu 4 cm jääsauva ja ajanmittauslaitteisto, joka automaattisesti katkaisee ajan mittauksen langan mentyä läpi ja painon pudottua kytkimelle. Lankojen sähkönjohtokyky määritettiin kokeellisesti ja sen avulla laskettiin lämmönjohtavuuskerroin käyttäen Wiedemsás lakia.

Hypoteesina oli, että lämmönjohtavuuskertoimeltaan paremmat langat myös läpäisevät jääsauvan nopeammin ja että lämmönjohtavuuskertoimen ja mitatun läpäisyajan välillä on korrelaatio.

Tulokseksi saatiin, että lämmönjohtavuuskertoimen ja ajan välinen suhde käytetyillä langan ja sauvan paksuuksilla mittauslämpötilassa 18.5 °C on $\mathrm{t} = (-6.78 \pm 0.82)\mathrm{k} + (273 \pm 15.7)$ missä *t* on aika minuutteina ja *k* lämmönjohtavuuskerroin yksikkönä $\frac{W}{m \cdot K}$. Tämä malli pätee vain lankoihin joiden lämmönjohtavuuskerroin on alle $40\frac{W}{m \cdot K}$. Tutkimusta voisi parantaa useammilla toistoilla sekä käyttämällä useampia lankoja, joiden lämmönjohtavuuskertoimet ovat laajemmalla alueella.

ABSTRACT

In this study the effect of the material on the speed of a metal wire passing through a block of ice is studied experimentally. The experiment was conducted at room temperature using 2 mm wires and 300 g weights, because the process was found out to be nonexistent in the freezer. The times were measured using an apparatus consisting of a stand and an automatic system for ending the time measurement when the wire has passed through. This was achieved by attaching a switch directly below the weights, which was switched off when they fell. The hypothesis was that the material affects the speed notably and that there is a correlation between the thermal conductivity of the metal and the time it takes to pass through. It could be concluded that the material indeed affects the speed of the wire passing through the block of ice. The relationship between thermal conductivity and time taken under the conditions of this experiment was found out to be $\mathrm{t} = (-6.78 \pm 0.82)\mathrm{k} + (273 \pm 15.7)$, in which t is the time in minutes it takes to pass through and k is the thermal conductivity value of the wire in $\frac{W}{m \cdot K}$. However this model only fits in the range of k less than $40\frac{W}{m \cdot K}$, temperature of 18.5 °C, using wires of 2 mm diameter, 300g weights and ice rods of 4 cm in diameter. The results could be improved through use of materials with more varying thermal conductivities and by conducting the experiment in an environment with controlled temperature .

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1. INTRODUCTION

As a phenomenon regelation has been known for quite a while, but has been neglected for quite a time. Among the first to suggest that a thin film of liquid covers the surface of ice even below the point of freezing was Michael Faraday back in 1859 (Rosenberg, 2005).

The popular theory of pressure lowering the melting point dates back to 1850 when James Thomson studied the relationship between pressure and melting point and found out that it was linear, resulting in a downward-sloping straight line. This is one of the rather interesting properties of ice; usually increased pressure raises the melting point, however because ice is less dense than water (this is why ice floats on water), according to LeChatelier's principle increased pressure moves the equilibrium state to the direction of the less dense matter to counteract the effect of increased pressure. (Weast, 1975, F-105)

Based on Thomson's results John Joly proposed in 1886 that the pressure caused by the skates on the ice is responsible for the melting of the water. Joly's argument was that the area of the blade touching the ice is so small that it causes a high pressure. The pressure that he calculated was 466 atm and resulted in melting point of -3.5 °C. This raises the question of what had been the area of the blade that Joly had used.

If we assume a 50-kg person on the skates and that the pressure is Joly's 47 205 800 Pa. Because $p = \frac{F}{A} = \frac{mg}{A}$ the area is ~0.000001 m^2. If the blade is 0.25 m long, the width of the blades is 0.000004 m. Assuming a modern skate with two sharpened edges in each skate, the width of one can be calculated to be 0.000001 m, or 1 µm. This is an extremely small width, and yet it only accounts for skating in -3.5 C or more. In his book Nurmi (1971) states that the melting point is approximately lowered by 0.0075 °C when the pressure increases 1 atm (or 101300 Pa), and at 1000 atm is approximately -9 C. If a person were to skate in -9 C, he would have to have blades 0.5 µm wide to create the required 1000 atm pressure, assuming that the other variables are kept constant and only the pressure affects the melting. However skating is possible in temperatures that are even lower than -9 °C. This same flaw is pointed out by Rosenberg (2005).

The process of a wire passing through an ice block leaving it intact is based on the same principles as skating and is nowadays a popular demo, for example University of Wisconsin-Madison (Chemistry Department) and University of Washington (Physics Department) have this demo as well as but the phenomenon is solely credited to effect of pressure on the melting point on ice. The fact that the same explanation is given in some Finnish high school physics textbooks (e.g., Lehto & Luoma, 1999, 63; Eskola et al., 2000, 89). However in 1963 J. W. Telford and J. S. Turner conducted similar experiments to the demo in which they found out that the increase of velocity of wire passing through the ice corresponded linearly to the surrounding temperature until they reached the point at which the pressure caused by the wire on the ice started to be responsible for melting.(Rosenberg, 2005)

While the demo well illustrates the phenomenon, it indeed has some notable flaws in design: The process is often done at room temperature using a metal wire, so the effect of heat conduction should be taken into consideration when the results are evaluated. The intention is to do a similar experiment to the demo of wire passing through an ice block, which focuses on the effect of material by keeping the other factors constant while varying the material.

Hence the research question: *How does the material of wire affect the speed of wire passing through an ice block?*

It could be hypothesized that the melting is caused by the heat conducted by the wire from the surroundings, and the refreezing is caused by metal conducting the heat from water above it to the ice below instead of the pressure of the wire lowering the melting point. The refreezing would be caused by the heat from water being conducted to surrounding ice. This idea is presented for example by the University of Maryland in conjunction with the procedure of the demo (see p. for the link). Hence the hypothesis is that the material of the wire affects the speed of the demo, *being the fastest with the wire with the highest heat conductivity, k*. This is implied in an A-level physics book by the phrase "Why will the experiment [on regelation] not work if string is used rather than a copper wire? "(Gibbs, 1990, 237)

Because the wires are alloys instead of pure substances, there are no thermal conductivity values available for them. Hence these values must be determined experimentally for the very wires used.. According to Wiedemann-Franz law

(1) $\frac{k}{\sigma} = LT$,

in which k is the thermal conductivity of the wire, σ is the electrical conductivity of the wire, L is the Lorenz number 2.45×10^{-8} W·Ω·K^{-2} and T is the temperature in kelvins, the thermal conductivity can be calculated if the electrical conductivity is known. (Nave, 2006) This can be achieved indirectly by measuring the resistance of the wires and using the obtained values to calculate electrical conductivity, σ. After this the thermal conductivity can be calculated using Wiedemann-Franz law.

2. MATERIALS AND METHODS

2.1 APPARATUS

2.1.1 FOR MEASURING THE TIME OF PASSING THROUGH

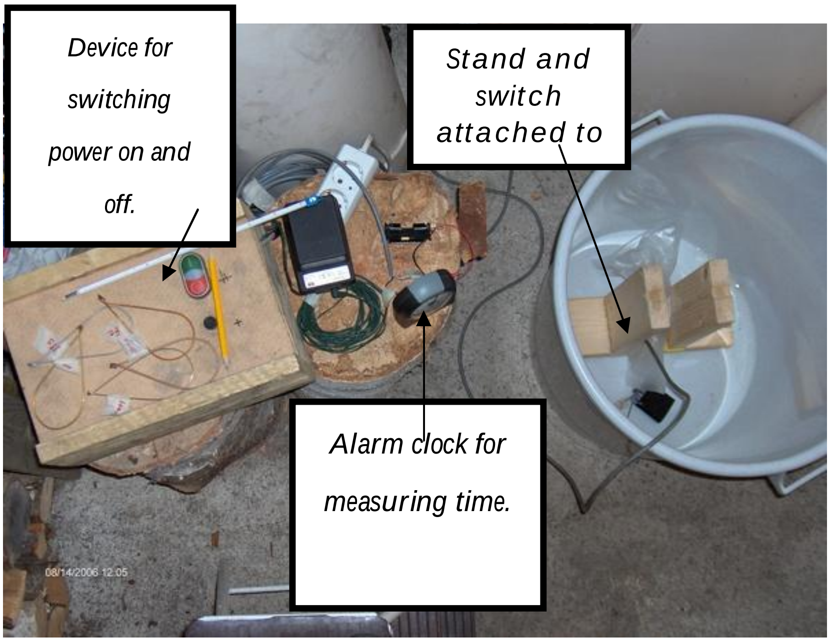

FIGURE 1 A PICTURE OF THE APPARATUS USED.

The apparatus needed for measurements on the effect of material is rather simple, consisting of a stand for ice, a device for measuring the time, something to make ice in, weights and various wires. Ice rods were at first made in a length of tube with 2 cm radius.

The stand was made from wood because it is readily available, a rather poor heat conductor and easy to work with. Approximately meter's worth of plank was used to create the stand of sufficient height (25 cm). First a piece of 50 cm was measured, then the centre of this bit was located and a hole with radius of 2 cm was drilled through the centre. The purpose of the hole is to keep the rod of ice in place, so that it would not roll off the stand during the experiment. Then the 50 cm piece was cut in half creating two identical 25 cm pieces each having a semicircle at one end. After this, the 25 cm planks were nailed to another plank which served as the base of the stand. A piece of 2”x2” was fitted between the vertical planks to allow the attachment of the switch to the stand. The stand was located to the bottom of a container to reduce the effect of convection on the results.

The wires used are welding wires of approximately 2 mm in diameter. This is because they were easily available to use and have known compositions (Appendix). The materials are aluminium, phosphorous copper, brass, silver, steel and stainless steel. These have different thermal conductivity values, which should affect the speed of passing through.

The device for measuring time consists of an alarm clock and a switch that cuts the power on and off from the clock. A normal stopwatch could have been used instead of this more complex system, but then there would have been the risk of the weight destroying the stopwatch when it falls to stop the clock. Hence this system of remote switching was adopted for the measurements. Active circuit (one that requires electricity to function) was used for the relay switching of the alarm clock because it seemed to be the most reliable and accurate, and the clock doesn’t run after the power is cut off.

2.1.1 APPARATUS FOR DETERMINING THE THERMAL *CONDUCTIVITIES*

The equipment needed is a voltmeter (precision ±0.1 mV), an ammeter (precision ±0.01 A), a metric measure, a micrometer, leads to connect the wires and clamp connectors to connect the wires to the circuit, four 22 Ω resistors and a variable DC power supply.

The diameters of the wires were measured using a micrometer screw gauge, which has accuracy of ±0.005 mm. The lengths of wires were measured using an ordinary metric measure with the precision ±0.005 m.

The resistors were connected in parallel (Figure 2.), because it was expected that the current would be relatively high. By connecting them in parallel the current would be divided between the different resistors, effectively resulting in a capability to use higher current without fear of melting the resistors. Also because the resistance of the wire is known to be very small, the resistors connected in parallel allow low resistance with aforementioned ability to use high current.

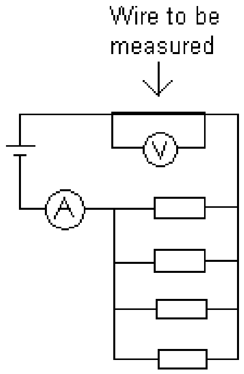

Figure 2. Illustration of the circuit of the apparatus

2.2 PROCEDURE

2.2.1 DETERMINING THE EFFECT OF MATERIAL

The procedure for measurements is relatively simple: The wire loop is put around the block of ice, the weight is attached to the loop the ice block is set to the stand and the circuit is closed (i.e. the button on the power supply is pressed), effectively starting the clock. The rest of the process is waiting, and the clock stops itself when the weight falls on the switch after the wire has passed through the block of ice. Then the time is marked down, the clock is zeroed to "midnight" and a new is rod is prepared for testing with different wire. The temperature is measured during the experiment to ensure that there are no abnormalities. Then the procedure is repeated. The thermometer was calibrated in water filled with ice cubes; the thermometer showed accurately 0 °C so there was no systematic error (it was needless to calibrate with more points because the measured temperature only has to be approximately the same for all the measurements, say, 17-19 °C).

2.2.2 FLAWS FOUND IN THE PROCESS

During test runs it was found out that the 2 cm diameter is too small, and the rods of ice broke before the wire could fully pass. Hence thicker rods had to be used. With 4 cm diameter ice rod there was no breaking, so the final measurements were done using them.

Also at first the idea was to conduct the experiment in a freezer, at -18 °C. When the test run was done it was observed that the 2 mm wire didn't pass through the ice block at all during the 48 hours of observation, so the experiment was moved to the garage, wherein there is an almost constant temperature during the course of a few days and the temperature is high enough to make the wire pass. Hence the results of the same series of tests are comparable and the measurement time stays humane.

After a couple of measurements in the garage it was observed that the switch starts to behave quirkily when wet and the apparatus for time measurement refused to start. Luckily it only affected the starting of the clock, and wouldn't stop the time measurement even if the switch is exposed to water during the course of the measurement. The problem, however, was easily overcome by covering the switch with a plastic bag, effectively waterproofing the circuit. The bag was placed so that there wouldn't be any puddles formed and no error caused by the water masses closing the switch prematurely. After this there were no problems whatsoever in measuring the time.

2.2.2 DETERMINING THE THERMAL CONDUCTIVITY VALUES FOR THE ALLOYS

When the apparatus had been made, the voltage from the power supply was varied so that the ammeter reading would be approximately 0.20, 0.40, 0.60, 0.80 and 0.95. With each current the exact current was recorded with the respective potential difference between the ends of the wire. The same procedure is repeated for each wire. The clamps should be as close as possible to the ends of wire so that the effective length of wire that causes the resistance is as close as possible to the full length. Also it should be made sure that the connection between the clamp and the wire is good. This can be ensured by applying notable force on the clamp so that the surfaces in contact are firmly squeezed together.

3. RESULTS AND ANALYSIS

3.1 RESULTS

3.1.1 THE TIMES OF PASSING THROUGH

As stated before, the 2 mm wire didn't pass through at all at -18 °C. Hence it can be concluded that at these diameters the water layer on the surface of the ice isn't thick enough to give rise to regelation and there isn't enough heat in the surroundings to be conducted to melt the ice. However in the garage the measurements gave varying data, which lends itself to closer analysis.

Table 1. The measured values of the experiment on the effect of the material. Both series were measured at approximately 18.5 °C (minor fluctuations in the scale of ± 1°C). A rough estimation for the uncertainty was calculated using $\frac{t_{\max} - t_{\min}}{2}$ for each wire separately.

Material of Wire	t_1 (min)	t_2 (min)	t_{mean} (min)	uncertainty
Silver	183	155	169	±14
Aluminium	85	73	79	±6
Phosphorous copper	169	175	172	±3
Steel	163	171	167	±4
Stainless Steel	255	245	250	±5
Brass	103	127	115	±12

The ice rods were all initially -18 °C. It took approximately 260 minutes for the ice rod to melt in this environment.

3.1.2 THE MEASUREMENT FOR THE THERMAL CONDUCTIVITY

When the measurements had been done the following results were achieved. Table 2. has the results of the measurement including the electric circuit, whereas Table 3. has the measured dimensions of the wires. The compositions of the wires were known, but couldn´t be used to define thermal conductivity.

Table 2. Currents and their respective potential differences measured.

Al wire		Ag wire		Brass wire	
I(A) ±0.01	V(mV) ±0.1	I(A) ±0.01	V(mV) ±0.1	I(A) ±0.01	V(mV) ±0.1
0.21	3.0	0.23	5.7	0.18	4.2
0.40	6.2	0.40	9.2	0.44	9.8
0.60	10.2	0.63	14.2	0.60	12.8
0.80	12.1	0.78	21.0	0.78	19.3
0.95	14.4	0.94	22.7	0.95	21.2
Stainless steel wire		PCu wire		Steel wire	
I(A) ±0.01	V(mV) ±0.1	I(A) ±0.01	V(mV) ±0.1	I(A) ±0.01	V(mV) ±0.1
0.20	18.2	0.17	4.4	0.23	8.0
0.38	29.0	0.40	10.6	0.40	13.2
0.64	52.0	0.60	16.4	0.58	17.7
0.80	67.0	0.82	19.5	0.82	24.7
0.94	90.4	0.95	23.4	0.95	28.9

Table 3. Measured thicknesses and lengths of the wires used.

	Thickness (m) ±0.00005	Length (m) ±0.005
Al wire	0.00196	0.196
Ag wire	0.00143	0.199
Brass wire	0.00195	0.197
Stainless steel wire	0.00198	0.196
PCu wire	0.00234	0.197
Steel wire	0.00195	0.196

3.2 ANALYSIS

3.2.1 CALCULATING THE THERMAL CONDUCTIVITIES

The results in Table 2. were plotted to a graph and a line was fitted to the points using the Least Square Fit –method (see Fig 3. for example).

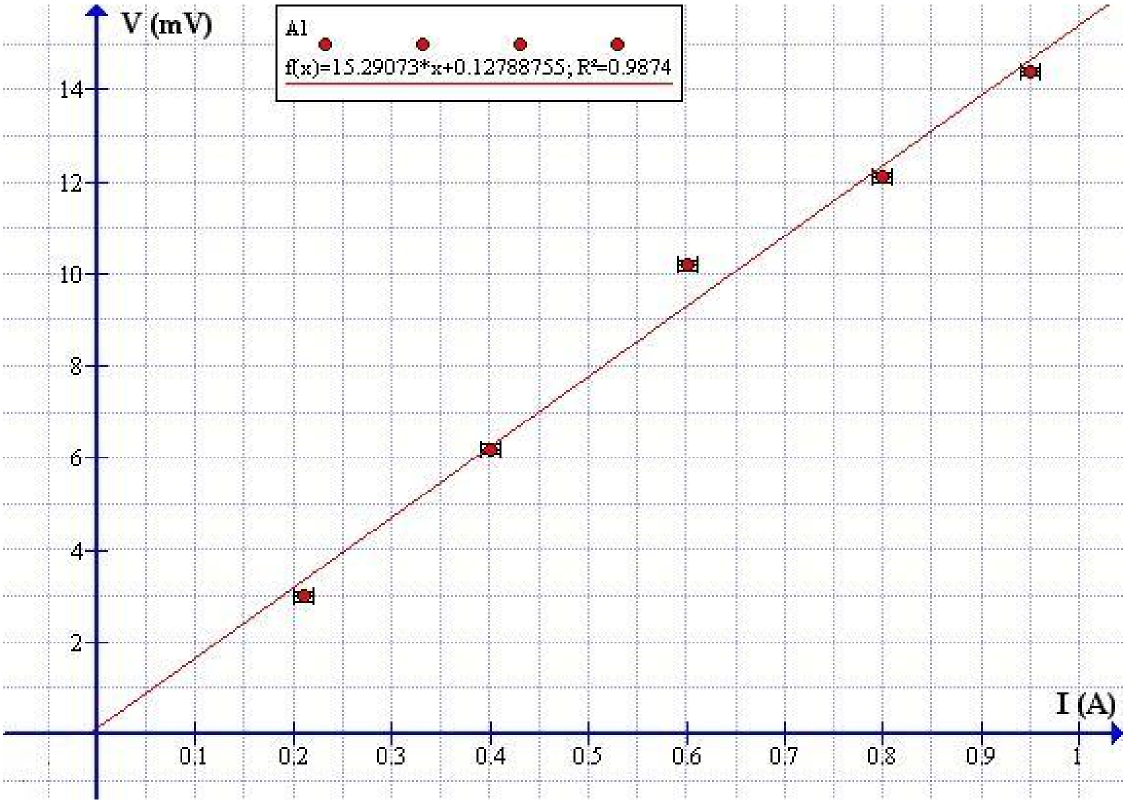

FIGURE 3. THE GRAPH PLOTTED FOR THE AL WIRE.

The gradient of the fitted line is the resistance of the wire of that length and diameter in milliohms. The uncertainty for this value is given by the fitting program programmed into the calculator. Because the least accurate value was with two significant figures, the uncertainties were rounded to two significant figures and after that the values to the same amount of digits.

Now the electrical conductivity can be calculated using (2) $\sigma = \frac{l}{R \cdot A}$,

in which R is the resistance in of the wire in Ω , A the cross-sectional area in m² and l the length in m. (Gibbs, 1990) Because the wires are round the cross-sectional area is $\frac{\pi \cdot d^2}{4}$. For example for aluminium the calculation goes:

Table 4. The resistances for the wires.

Material	R (**Ω**)
Al wire	0.0153 ± 0.0010
Ag wire	0.0254 ± 0.0023
Brass wire	0.0231 ± 0.0018
Stainless steel wire	0.0948 ± 0.0090
PCu wire	0.0237 ± 0.0015
Steel wire	0.0286 ± 0.0060

$$\sigma = \frac{4 \cdot (0.196 \pm 0.0005)m}{(0.0153 \pm 0.0010)\Omega \cdot \pi \cdot ((0.00196 \pm 0.000005)m)^2} = 4250000\ \Omega^{-1} m^{-1}$$

The uncertainty is calculated by adding up the relative uncertainties i.e. for aluminium $\left(\frac{4 \cdot 0.0005m}{0.196m} + \frac{0.0010\Omega}{0.0153\Omega} + \pi \cdot \left[\frac{0.000005m}{0.00196m} + \frac{0.000005m}{0.00196m}\right]\right) \cdot 100\% = 9.2\%$

This was done for all the materials with their respective values.

Now, according to Wiedemann-Franz law

(1) $\frac{k}{\sigma} = LT \Leftrightarrow k = LT\sigma$,

which can now be calculated. For example for Al:

$$k = LT\sigma \Rightarrow k = 2.45\times10^{-8}\ \mathrm{W{\cdot}\Omega{\cdot}K^{-2}} \cdot 291.5K \cdot 4250000\Omega^{-1}m^{-1} \approx 30.4\frac{W}{m\cdot K}$$

The uncertainty for *k* is the same as for $\boldsymbol{\sigma}$ because it is basically $\boldsymbol{\sigma}$, which is multiplied with constants. Hence the percentage error is the same. These values are in Table 5. No alloys with similar compositions could be found neither in CRC Handbook or MAOL, which makes the evaluation of results hard.

Table 5. σ- and *k*-values calculated.

Material	$\boldsymbol{\sigma}$ ($\Omega^{-1}m^{-1}$)	*k* ($W\cdot m^{-1}K^{-1}$)
Aluminium	4250000 ± 9.2%	30.4 ± 9.2 %
Silver	4880000 ± 12.3%	34.9 ± 12.3 %
Brass	2860000 ± 10.4%	20.4 ± 10.4 %
Stainless steel	671000 ± 12.1%	4.8 ± 12.1 %
Phosphorous copper	1930000 ± 8.7%	13.8 ± 8.7 %
Steel	2300000 ± 23.6 %	16.4 ± 23.6 %

3.2.2 COMPARING THE THERMAL CONDUCTIVITIES WITH THE MEASURED TIMES

When the mean times in Table 1. are compared to the *k*-values of table 4. (Figure 4.) it can be observed that there is a seems to be a definite link between the thermal conductivity and time of passing through the block; as the thermal conductivity increases the time it takes to go through the block apparently decreases linearly. However the point of Ag-wire differs highly from the observed trend. This could be partially explained with the smaller diameter of the wire, which was not know until it was measured; because the wire has smaller area of conduct it can conduct less heat, effectively melting less ice. If this obviously erroneous value is neglected a line can be fitted to the points using the Least Square Fit method.

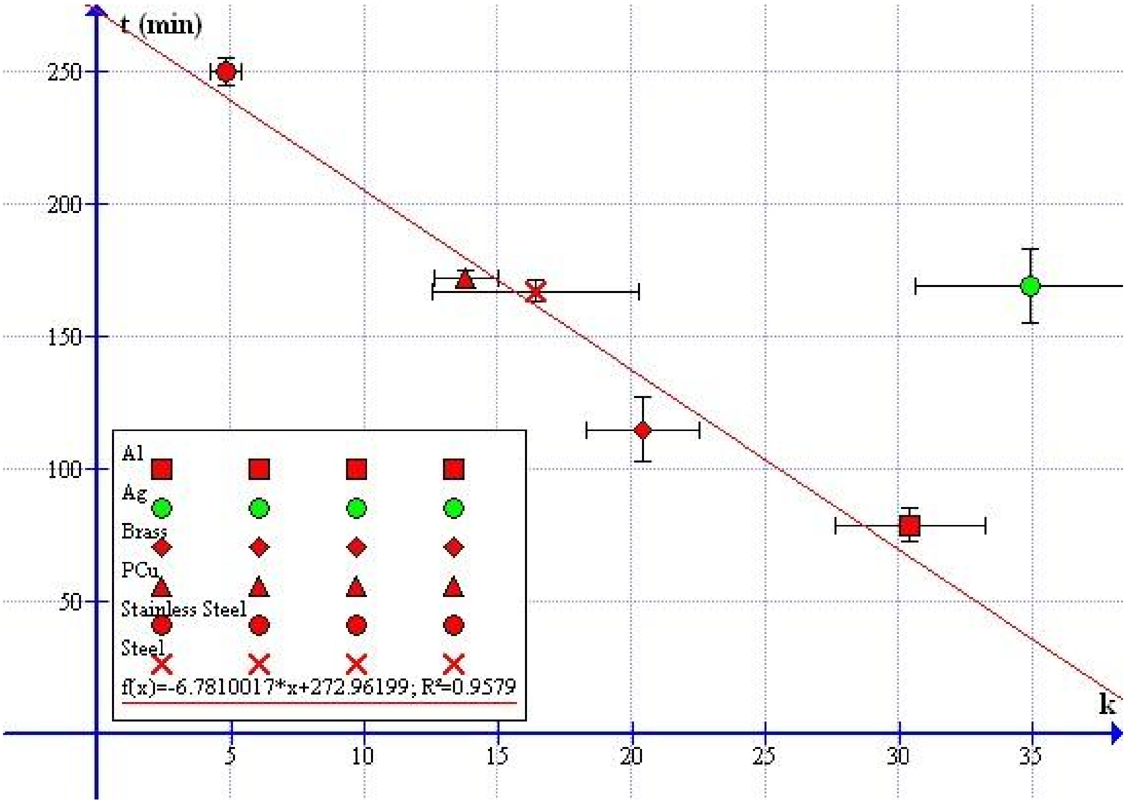

FIGURE 4. TIME PLOTTED AS A FUNCTION OF *K*. THE LINE WAS NOT FITTED THROUGH AG (EXTREME RIGHT) BECAUSE IT SEEMED TO BE A FLAWED RESULT.

The line fitted is $t = (-6.78 \pm 0.82)k + (273 \pm 15.7)$, in which t is in minutes and *k* in $\frac{W}{m \cdot K}$. This seems to correlate very well with the results, because when k=0 the time is 273 ± 15.7 min, while the time it took for the whole block to melt all by itself was approximately 260 min, which is within the uncertainty.

4. CONCLUSIONS AND EVALUATION

4.1 CONCLUSIONS

The experiment on the effect of material showed that the material and moreover the thermal conductivity indeed plays an important role in the popular demo of wire passing through a block of ice; as thermal conductivity increases the time taken decreases. The relationship in this experiment was found out to be $\mathrm{t} = (-6.78 \pm 0.82)\mathrm{k} + 273 \pm 15.7$, in which t is in minutes and *k* in $\frac{W}{m \cdot K}$. The hypothesis was indeed correct, and the material should be taken into consideration when evaluating the results of a regelation experiment. However, the expression found cannot be applied to general cases, because te line cuts the x-axis, which should be an asymptote for the curve, because the thermal conductivity should be infinite for the wire to pass through immediately. Also this model cannot explain higher values of *k* , for example approximately 401 $\frac{W}{m \cdot K}$ (Barbalace, 2006) of pure copper.

The thin film of liquid water doesn't seem to have a great impact on the results of these experiments, because the stainless steel wire hardly penetrated the surface of the ice, instead of the passing through the block caused by the water layer always which could have been expected. This might be caused by the fact that the experiments were done at room temperature and with rather thick wires with respect of the thickness of water layer, that is, the layer is not thick enough to allow 2mm wires to pass through the block.

4.2 EVALUATION

The experiment was partially a success. It could be shown that there is a relationship between time taken and thermal conductivity of the wire, also a linear relationship could be established between the results. Using more diverse materials with more varying thermal conductivities and more repetitions a more accurate model could be formulated. However because the experiment is done above the melting point of ice, the melting of ice with the aid of heat from air will somewhat affect especially the results in the lower end of k-spectrum, i.e. less conductive materials, decreasing their time. Hence the model is correct only in a very narrow spectrum of thermal conductivity at 18.5 °C and using 2mm wires and ice blocks with 4 cm diameter.

The apparatus and procedure were successful. With the aid of the vat the effect of convection on the temperature could be minimised and after the initial difficulties the time-measuring device functioned reliably and accurately. As an improvement the experiment could be done in an environment with controlled temperature e.g. a large refrigerator. Also more measurements should be done, two measurements per wire showed surprisingly much variation in the time of passing through the block of ice.

The uncertainties were feasible, averaging at 10%. Taking into consideration the conditions under which the experiment was conducted and the materials used, it is satisfactory. The uncertainties of *k*-values could have been decreased by doing more measurements on the resistance, but this was limited by the power supply and the accuracy of the ammeter. If a more accurate ammeter and a power supply with more accurate adjustment had been used the uncertainty of *k* would have decreased, decreasing the uncertainty of the fitted line.

4.3 FUTURE EXPERIMENTS

Some study on the effect of pressure was done, which could be done in more detail. As a hypothesis the relationship between the pressure and the time shouldn't be linear, because the increased pressure only lowers the melting point in the magnitude of a couple of degrees at most. The drastic decrease in the time with the increased pressure that was observed could be better explained by the additional force dragging the wire through the semi-liquid layer of the ice than by decrease of melting point. However based on so few results formation of hypothesis is fallible.

Also considering the theory of water layer present on the surface it can be hypothesized that the diameter of the wire affects the speed of the wire. If the wire is approximately of the same thickness as the water layer, the speed should be greater than with a thicker wire, because less energy must be conducted by the wire to free the molecules from the lattice structure on the border of the ice due to the smaller amount of particles needing the energy and greater proportion of the being already free of the lattice.. Therefore an experiment could be conducted on the implication of Gibbs (1990), to determine whether at certain diameters the material does matter or not. As a hypothesis a wire in the correct scale of diameter should pass through independent on the material of the wire.

Some experimentation was done in the side of the main research on the effect of diameter. The statement that the nylon wire would not regelate similarly to a metal wire (Gibbs, 1990) could not be proven false by the used thicknesses. Also an additional measurement with greater pressure and a wire thickness of 0.10 mm showed promise to shed light upon this aforementioned statement, for the pressure seemed to play a more major part than the thermal conductivity. Alas the nylon wire used in the experiments could not stand the weight of 300 g and results were not received. This leaves room for future experimentation on the effect of the pressure. More weights (e.g 50 g – 500 g) should be used to find out the relationship between the pressure and the speed, and the problem with breaking nylon string could be overcome using, for example, ultralight fishing line, which should be able to withstand greater stress than the string used and should come in the diameter of 0.10 mm.

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