

## 11. Problem №15: Heat and Temperature

### 11.2. Solution of Hungary

#### Problem №15: Heat and temperature

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#### The Problem

*A tube passes steam from a container of boiling water into a saturated aqueous salt solution. Can it be heated by the steam to a temperature greater than 100°C? Investigate the phenomenon.*

#### Abstract

Heating of the saturated salt solution to its boiling point of 108.5 °C with 'cool' steam of temperature 100 °C seems to be impossible. Experiments carried out show that this process takes place in reality. In this contribution the theoretical background of the underlying physical phenomenon is discussed. We have implemented quantitative measurements in order to verify the theoretical expectations. It turned out that the mass of the heated solution linearly increases with the increasing temperature. This finding implies that the necessary energy for the heating is originated from the condensation of the steam in the salt solution. The numerical values are in excellent agreement with the data found in standard tables.

#### 1. Introduction

Problem 15 addresses an interesting phenomenon. "A tube passes steam from a container of boiling water into a saturated aqueous salt solution. Can it be heated by the steam to a temperature greater than 100°C?" If this statement holds, for the first sight, it seems to contradict to the 'zeroth law of thermodynamics' which implies that "two objects in thermal equilibrium with each other are at the same temperature" [1]. Otherwise, heat is transferred from one object to another object as a result of a difference in temperature between the two. Normally the direction of the heat transfer is from the warmer object to the colder one. The strangeness of the phenomenon stands in the fact that the colder steam raises the temperature of the warmer solution.

In this paper the problem was investigated experimentally and theoretically as well. First preliminary experiments are described which gave answer to some technical problems such as how much salt is needed in order to keep the solution saturated or what the boiling point (maximum temperature) of the solution is. After that we discuss theoretical considerations, a possible explanation of the phenomenon. Detailed quantitative experiments are described henceforth, the tools, the setup, the measurements, the results and their statistical evaluation. Based on the above results finally the conclusions are drawn.

#### 2. Preliminary investigations

##### 2.1 Exploratory studies

In order to get the answers for some elementary questions first we made some experiments with the saturated salt solution heating it on a cooking-stove. It was important to know how

much salt we will need or what the boiling point of the solution is. It was clarified that the solubility of the salt increases with the temperature, so in our further experiments the saturation of the solution must be kept constant. It also became clear that the solution with excess salt in it, which assures it remains saturated during the experiment, boils at 108.5 °C, so this is the maximum temperature of the liquid we can expect when we are heating the solution by steam.

During some preliminary experiments it turned out as well that the solution can be brought to boil using steam too, so it reaches its boiling point of 108.5 °C.

These investigations showed that we must find an explanation for the seeming contradiction between the phenomenon and the 'second law of thermodynamics' and find out where the energy heating the solution above 100 °C comes from.

We have realized that in order to carry out precise measurements it is crucial to reduce the high heat loss to a minimum extent.

## 2.2 Theoretical considerations

When the steam is passed into the liquid a significant part of it condenses and the energy given up due to this phase change (latent heat), the heat of vaporization increases the internal energy of the solution. This consideration implies that under ideal circumstances the energy the steam loses ( $Q_1$ ) is equal to the energy the liquid gets ( $Q_2$ ), so the following equations can be used

$$\begin{aligned} Q_1 &= Q_2 \\ \Delta m_s \cdot L_v &= m_l \cdot c \cdot \Delta T \end{aligned} \quad (1)$$

where  $\Delta m_s$  stands for the mass of the condensing steam,  $L_v$  is the heat of vaporization,  $m_l$  is the total mass of the liquid,  $c$  is the specific heat of the solution and  $\Delta T$  is the increase of the temperature. With this relation we did not consider the heat that the condensed steam needs to get to the temperature of the salt solution, but in this case it is quite small and not a remarkable amount of energy.

If this theory describes the phenomenon we should answer the question as well that why the steam condenses. The explanation for the strange phenomenon can be found in the molecular level so we have to consider the arrangement of the ions and molecules in the solution and in the steam bubbles as well. At the creation of the steam pure water closes round the bubbles and the probability of entering a water molecule the steam  $P_{w \rightarrow s}$  is equal to the probability of leaving a water molecule the steam  $P_{s \rightarrow w} = P_{w \rightarrow s}$ .

But as we can see in Figure 1 the steam bubble in the salt solution is surrounded by sodium ions, chloride ions and water molecules making the surface through which water molecules can enter the bubble much smaller. This causes a reduced probability for entering a water molecule the steam from the solution  $P_{sol \rightarrow s} < P_{w \rightarrow s}$ . On the other hand, the probability of leaving a water molecule the bubble remains the same  $P_{w \rightarrow s} = P_{s \rightarrow w} = P_{s \rightarrow sol}$ . The resultant effect is that the probability of leaving a water molecule the steam bubble is larger than that of entering it. The molecules which leave the bubble give their kinetic energy to the liquid so its internal energy and its temperature increase.

According to this, the components of the system are *not in equilibrium*, so the 'zeroth law of thermodynamics' cannot be applied for this case. Furthermore, the phenomenon seems to contradict to the second law of thermodynamics as well, due to the unusual direction of the heat transfer. This argumentation, however, cannot be applied in this case as the second law of thermodynamics is only valid for *close* systems. The fact that the studied system is *open* is a crucial factor in understanding the physical background of the process.



### 3. Experiments

#### 3.1 Experimental tools and setup

For the further experiments we boiled distilled water in a retort, passed its steam to a thermos through a silicon rubber tube, used a thermometer and a digital scale to measure the temperature and the mass of the thermos filled with the solution. Figure 2 and Figure 3 show the real experimental arrangement and the schematic model of it, respectively. We needed a Styrofoam plug to reduce the heat loss in order to make precise experiments, but the solution remained in atmospheric pressure due to the hole on the plug. The salt solution was prepared by using distilled water and table salt.

#### 3.2 Measurements

The measurements were performed in several steps. First the steam of temperature 100°C was transmitted to the previously prepared salt solution. The saturation of the liquid was conserved during the heating by putting the necessary extra salt into the solution. As the temperature of the liquid reached 90°C the digital scale was set to zero. At each temperature increments of 1 °C the scale was read fifteen times. This was necessary because the thermos was shaking due to the bubbling and the values read from the scale had large fluctuations. This way we measured the temperature and the increment of the mass of the solution until boiling at 108.5 °C.

#### 3.3 Results

As the fifteen mass values at each temperature show large deviations, the average and standard deviation of these values were calculated then plotted against the temperature in the diagrams in Figure 4. The weighted *linear* fit of the mass averages determines the slope  $a$  which is the quotient of the mass of the condensed steam  $\Delta m_s$  and the increased temperature  $\Delta T$ . The linear connection between parameters  $\Delta m_s$  and  $\Delta T$  shows an excellent agreement with Eq. (1).

The diagrams in Figure 4 show the results of three experiments with the same solution. At these experiments the original mass of the solution, without the condensed steam, was the same. The appearance of the negative values can be explained with the large deviation as well. The last diagram shows a larger slope  $a$  than the others due to the larger heat loss during the experiment.

### 4. Conclusion

Our theory implies that the quotient of the condensed steam's mass  $\Delta m_s$  and the increased temperature  $\Delta T$  is constant  $a = \Delta m_s / \Delta T = m_l \cdot c / L_v$ , and the linear dependence of these parameters is clearly shown by the diagrams.

As a check of the validity of our results we can calculate the specific heat  $c$  of the saturated salt solution from the measured slope  $a$  as the equation shows.

$$c = a \cdot L_v / m_l \quad (2)$$

Using the slope from the first experiment the specific heat is  $c = 3.95 \text{ J/(g}^\circ\text{C)}$  which is very close to the value  $3.91 \text{ J/(g}^\circ\text{C)}$ , that can be found in standard tables for specific heat of the saturated salt solution at 0 °C.

These experimental results verify our theory that the steam condenses in the solution when it is bubbling through the liquid. The phenomenon appears when we are experimenting with

other salts as well. The heat of the dissolution does not influence the results significantly, only the heating time can change using other salts.

### 5. Acknowledgement

The author is indebted to Professors Z. Noszticzius and J. Pipek for the valuable discussions. The members of the Department of Materials Physics of the Loránd Eötvös University Zs. Rajkovits, L. Skrapits and P. Kenesei were also extremely helpful with the preparation for the 19<sup>th</sup> IYPT. The experimental tools were provided by the Kempelen Farkas Secondary School. The financial support of the Ministry of Education of Hungary is gratefully acknowledged.

### 6. References

[1] Serway RA, Beichner RJ. Physics for Scientists and Engineers with Modern Physics. 5<sup>th</sup> ed. Orlando FL: Saunders; 2000. p. 582.

### 7. Figures

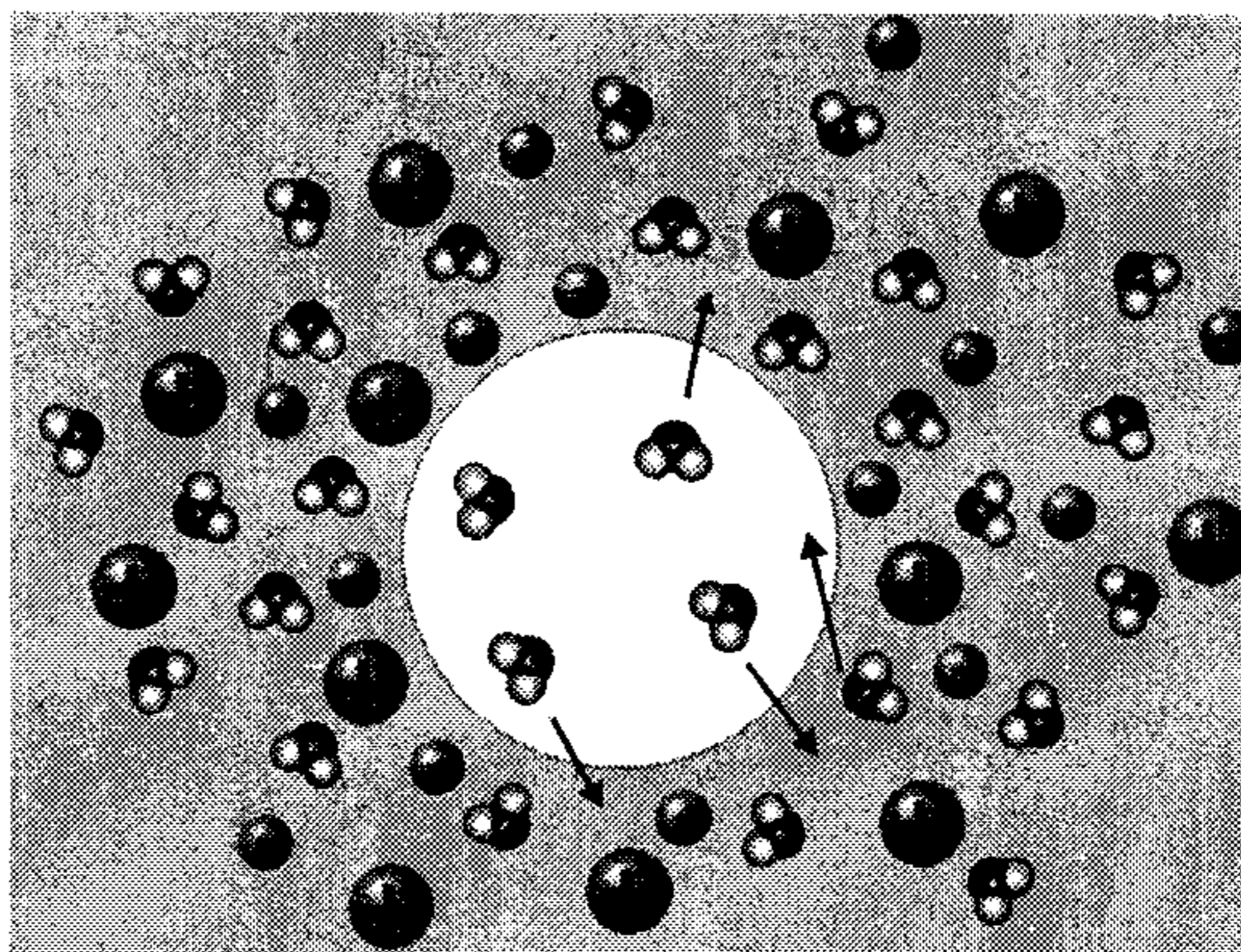


Figure 1. Molecular arrangement of water molecules and  $\text{Na}^+$  and  $\text{Cl}^-$  ions in a steam bubble and in the surrounding salt solution.



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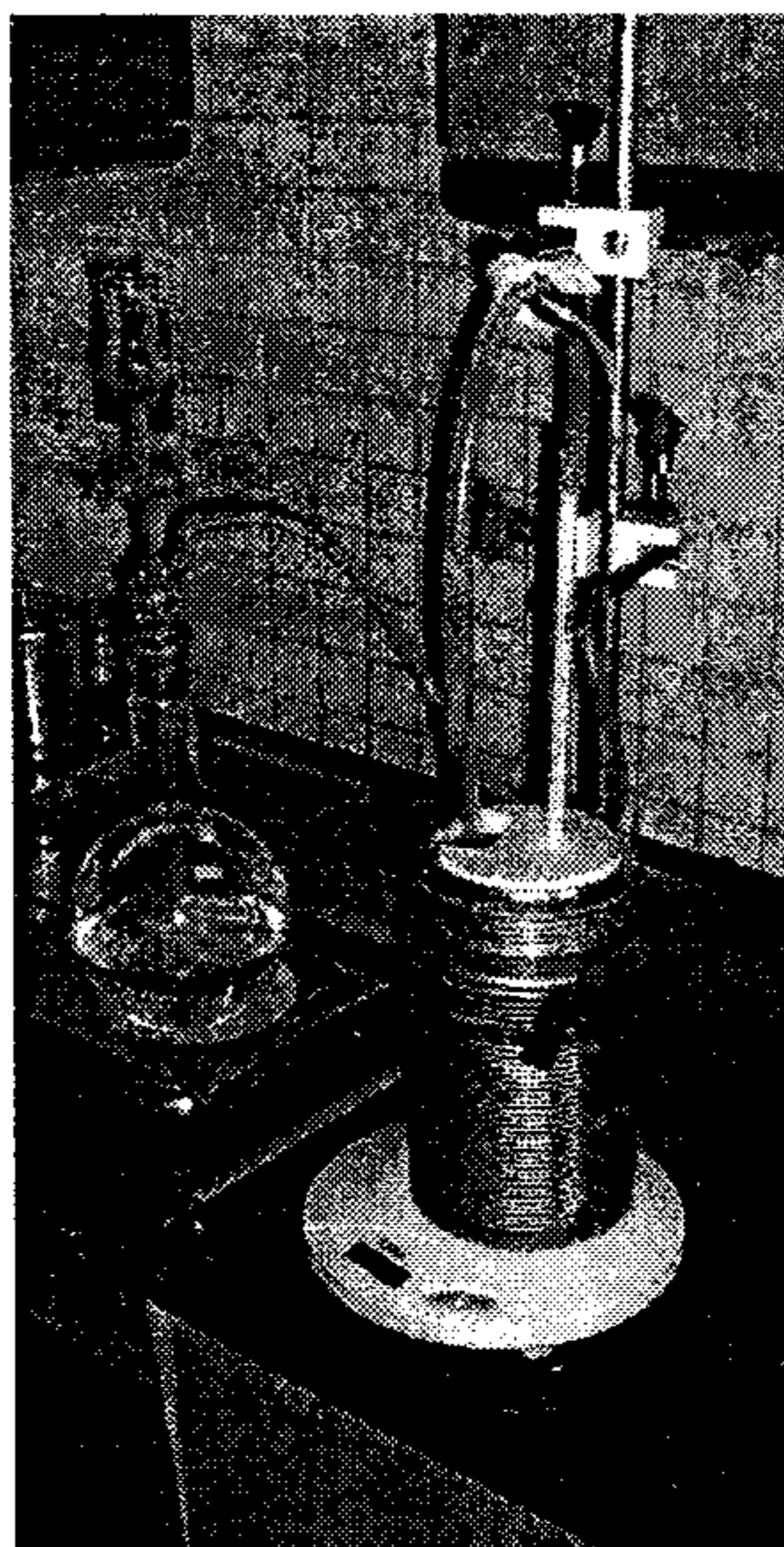


Figure 2. The experimental setup

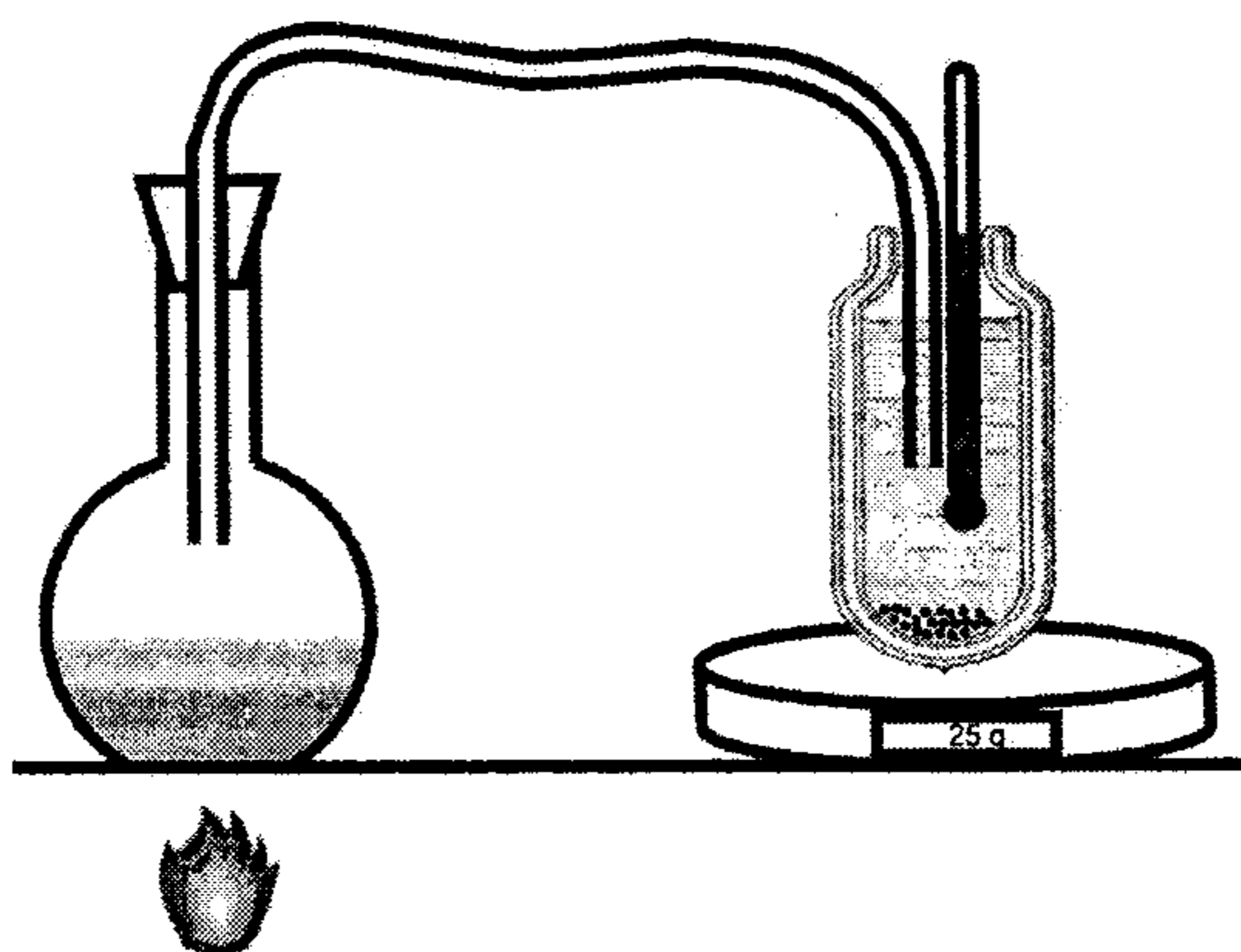


Figure 3. The scheme of the experimental arrangement.

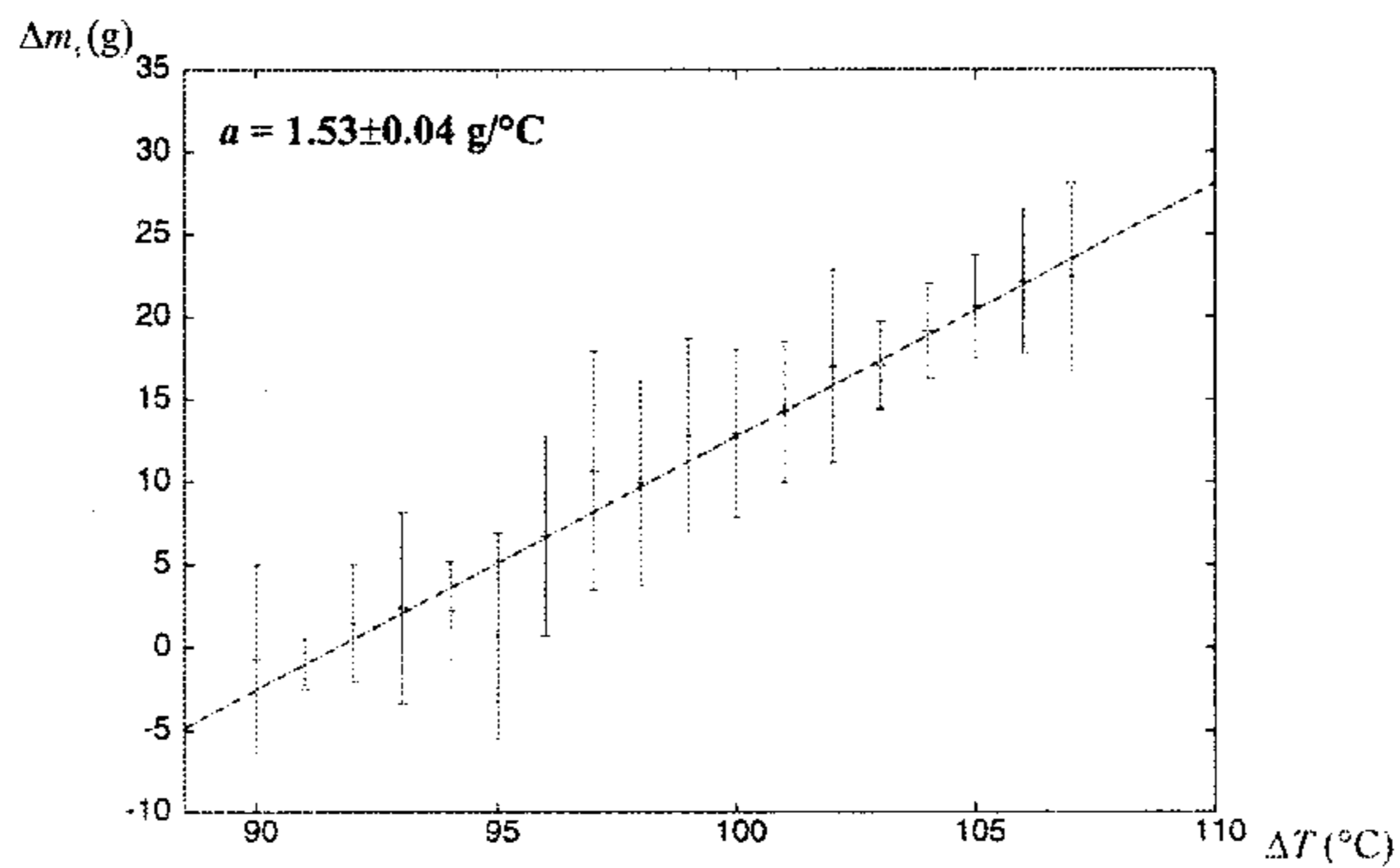
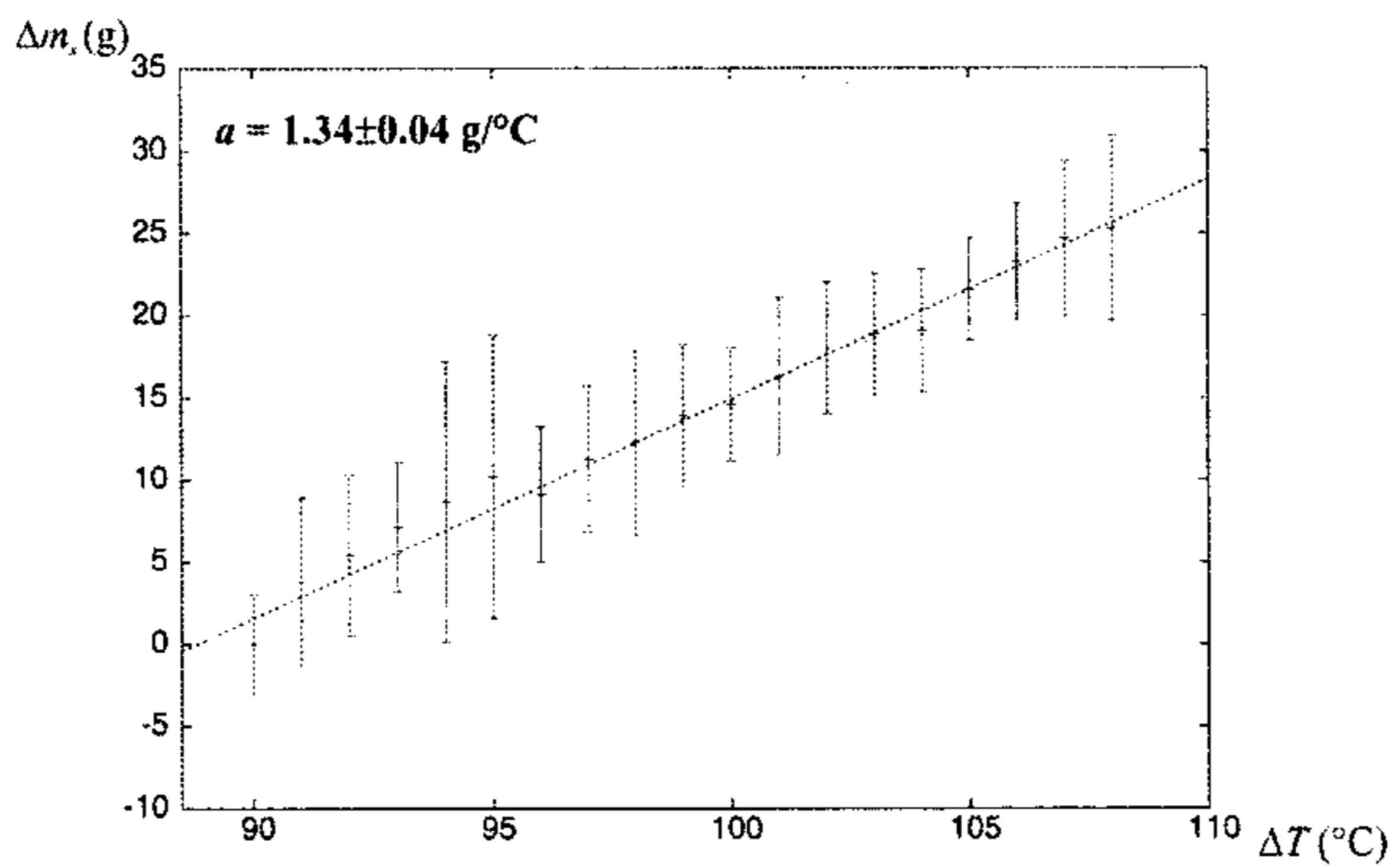
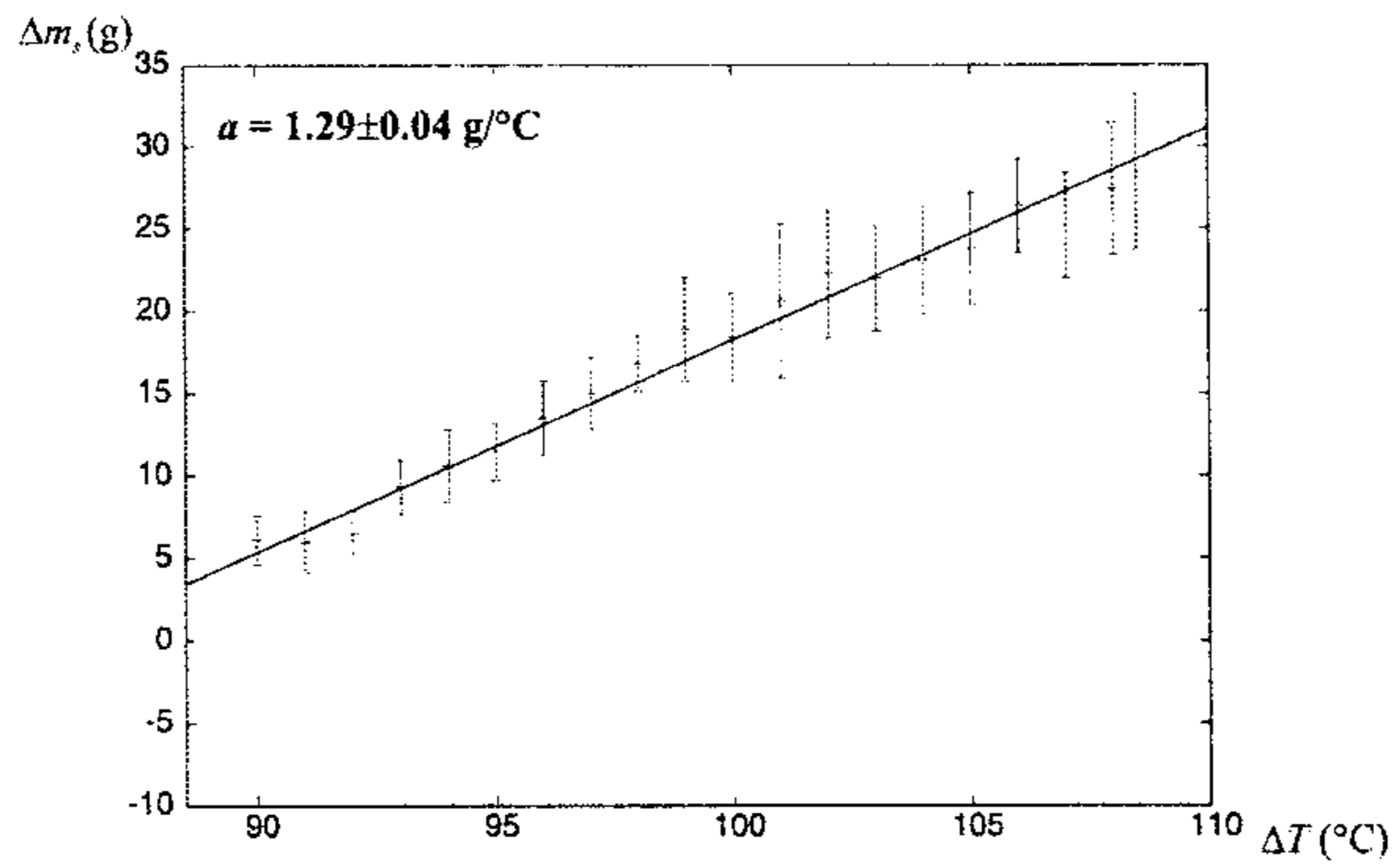


Figure 4. Increment of the mass of the salt solution with its temperature