

A SIMPLE LABORATORY EXPERIMENT WITH THERMOMETERS

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ABSTRACT:

A simple laboratory experiment with alcohol-glass thermometers is proposed in order to emphasize the priority of work procedure in the laboratory tasks. Results allow us to introduce some quite interesting questions about the involved concepts, such as thermodynamic equilibrium or empirical temperature, and to obtain a general view about the evaluation of the importance of the measurement process in the operational way in scientific thinking. The explicit aim of the experiment is to measure the temperature of a set of water samples with different amounts each. This is a simple but laborious task which leads to undoubtedly questions of interest in a twofolded way: firstly, the difficulty on stepping from relationships between the measured values and their reliability and accuracy, representation, critical analysis and performances required, which are common tasks in any laboratory experiment; secondly, the difficulties raised from the conceptualization of the measured quantities, operational definitions which are not currently taken into account in introductory physics courses. The comparison of experimental results with the theoretical explanation allow us to combine both rationale methods, coupling the involved concepts to required manipulations and the proposal of new improvements.

Keywords: Educational Research, Teaching methods, Laboratory task, Thermometry..

1.-INTRODUCTION

In the study of the historical evolution of the concept of temperature, there are many features that have considerable interest in the teaching of Thermodynamics (Smorodinski,1983). However, in the introductory physics courses, students generally arrive at this concept merely as a real number obtained from a thermometer -no matter its principle of operation, since its meaning is assumed meaning obvious to everyone-, that is further manipulated throughout thermodynamic laws, as a stellar quantity among others, and applied to a countless idealized and artificial problems.

Although this quantity, firstly introduced from thermometer reading, must be properly conceptualized, this can only be given, rigorously, in the framework of a thermodynamic theory. Thus, a proper definition of temperature is not at all achieved and needs actually a feedback process. According to this, the temperature is rather an evolutive concept with different subtle signification (Tisza,1966; Bridgman,1969) in different thermodynamic theories and, consequently, it is difficult to propose an adequate definition for introductory physics courses in order to avoid further and strongly established misconceptions. The axiomatic way on which thermodynamic theories are introduced (Callen,1985) has a clear and powerful logical structure, but an operational definition of temperature is quite often neglected. Moreover, for these courses, the axiomatic presentation is not at all adequate, being preferred the textbooks showing an inductive approach (Zemanski et al.,1997).

On the other hand, this is not only a proper characteristic of temperature but a general one that applies to all areas in Physics, which, at present, is not adequately emphasized in the physics teaching process (Cook, 1994). In the past recent years, there has been an increasing interest in developing new trends and ideas improving modes for the presentation of Physics. This task also can contribute to seeing physical education process in an unified way such as it is required from the Physics Education Research program (Fraser et al.,2014; McDermott, 2001).

The main aspects that can be denoted as priorities are:

- i/ The presentation of physics merely as a well-arranged and mathematical discipline should be avoided, keeping always in mind that it is strongly related to natural phenomena of the world where we live in (Arons, 1990; Romer, 1993; Larsson, 2017), and
- ii/ Physics begins with the observation of the real world, which can be analyzed and ordered, as far as possible, by means of mathematics, but which is always in evolution (Meltzer, 2004; Georgiou et al., 2015).

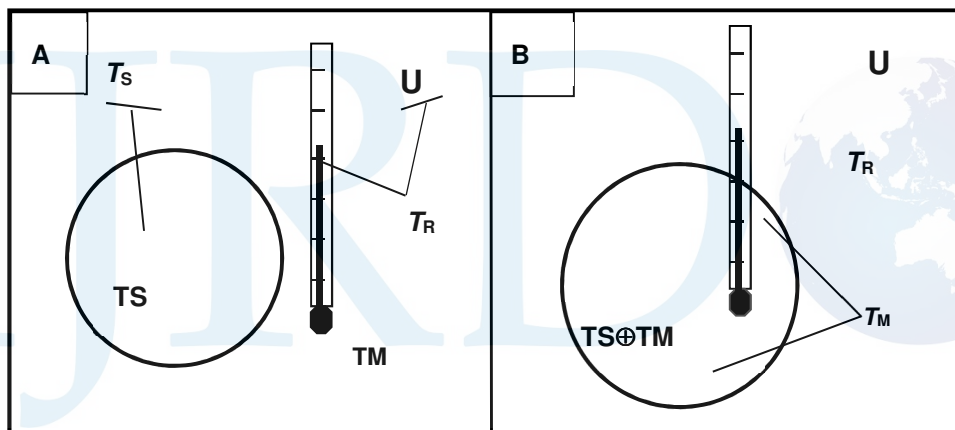
According to this, laboratory experiments -rather than elementary tasks which usually lead, in a strong way, to a unique result- become crucial for introductory physics teaching and, by means of them, students must acquire the ability to manipulate concepts, the way on these must be characterized as quantities, their relations, etc., instead of thinking of a problem or laboratory task as an effort to determine some unknown quantity, we ought to encourage students to think of the problems and task as an evolutive process (Larsson, 2017). Thus, presentation and development of realistic laboratory tasks, following these priorities, must be the main objective (Niaz, 2010). Therefore, there is a double

aim in this work: from a general point of view, it can provide the students a thorough overview of the most common formalities in the fulfillment of laboratory tasks and, in a specific way, it may introduce some criticism in the operational way from which the definition of temperature may be achieved.

2.-A SURVEY OF THEORETICAL BACKGROUND.

It is clear that the structure of physical theories is strongly determined by the nature and limitations of how we make measurements of basic quantities. The theories of special relativity, quantum and chaos are paradigmatic examples. The primitive physiological sensation of *hot* and *cold* that generates our crude concept of temperature, which has developed and used likewise, leads also to different thermodynamic theories (Tisza, 1966). Thus, its characterization is quite different for macroscopic thermodynamics of equilibrium (MTE), transport phenomena, or in statistical physics. The measurement of temperature, however, is achieved in all of them by similar methods.

FIGURE 1: Measurement procedure.



An examination of what is involved in the temperature measurement process shows that all thermodynamic principles are needed. This fact is not properly emphasized when making measurements. That is, in the measurement process, we have necessarily three systems: the thermodynamic system for which we measure temperature (**TS**), the system that acts as a thermometer (**TM**), and the universe (**U**) they lie in, as it is depicted in Figure 1a. The zeroth principle ensures the existence of a state of equilibrium for the isolated system. The first principle provides the adequate interchange of energy between the two systems involved in the measurement process, it ensures that the increase of work dilatation is found to be exactly equal to the heat transfer involved in the operation of 'thermal contact' (represented by \oplus , in the following) between the system and the thermometer: $TS \oplus TM$; and, finally, the unity of results in the comparison process is guaranteed by the second principle (Callen, 1985).

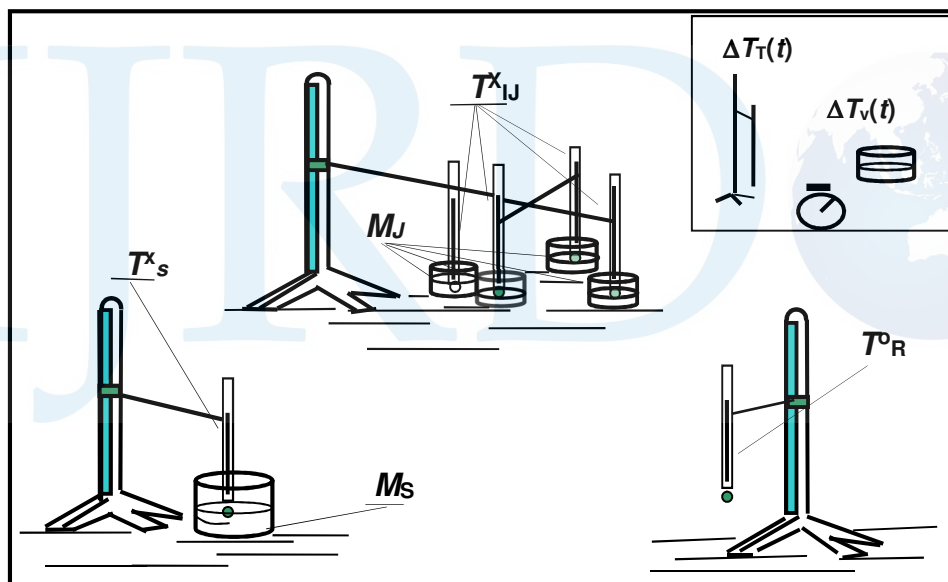
Thus, when we put the isolated system (**TS**), at the postulated temperature T_S , (system's temperature) in thermal contact with the thermometer, at the postulated temperature T_R (Room's

temperature), which is also the temperature of our laboratory room -the universe where it comes from-, they reach a new equilibrium state at the temperature T_M (**M**easured temperature)-zeroth principle-, unique -second principle-, which value is contained in the interval $[T_s, T_R]$ -Figure1b-; and it may be calculated with the help of the first principle [Tisza, 1966; Zemanski et al., 1997]. Elucidating the manner of energy exchange, which leads to external changes for an adequate thermometric property, is the main feature when building a good thermometer. This fact will be discussed below for our proper thermometric system. *Only if T_R is equal to T_s* , and the two systems in thermal contact are perfectly isolated, the true value can be really known. Nevertheless but this is real case, because virtual conditions of the postulation form are not at all achieved everywhere. These are:

a/ Thermal isolation of the systems implies that the postulated temperature is a constant value for all times; that is:

$$\frac{dT}{dt} \equiv 0, \forall t.$$

FIGURE 2: Experimental setup.



For real conditions, this restriction is only attained as nearly as possible; and it depends on τ_M , the time employed in the measurement, δT_M the accuracy of the apparatus, and τ_R , the time of response of the thermometer which must be close to τ_M (or the time of relaxation between the two systems in contact). Real isolation conditions may now be written as:

$$\frac{dT}{dt} < \delta T_M, \forall t > \tau_M; \text{ and } \tau_R \leq \tau_M$$

b/The nature and extension of the thermometric system, and its reference temperature T_R , must be connected in such a way that the difference between measured temperature T_M , and real temperature of the system T_s , is lower than the accuracy of the thermometer δT_M . Therefore, in the measurement process, T_s is not properly obtained; but there are some experimental conditions for which this value

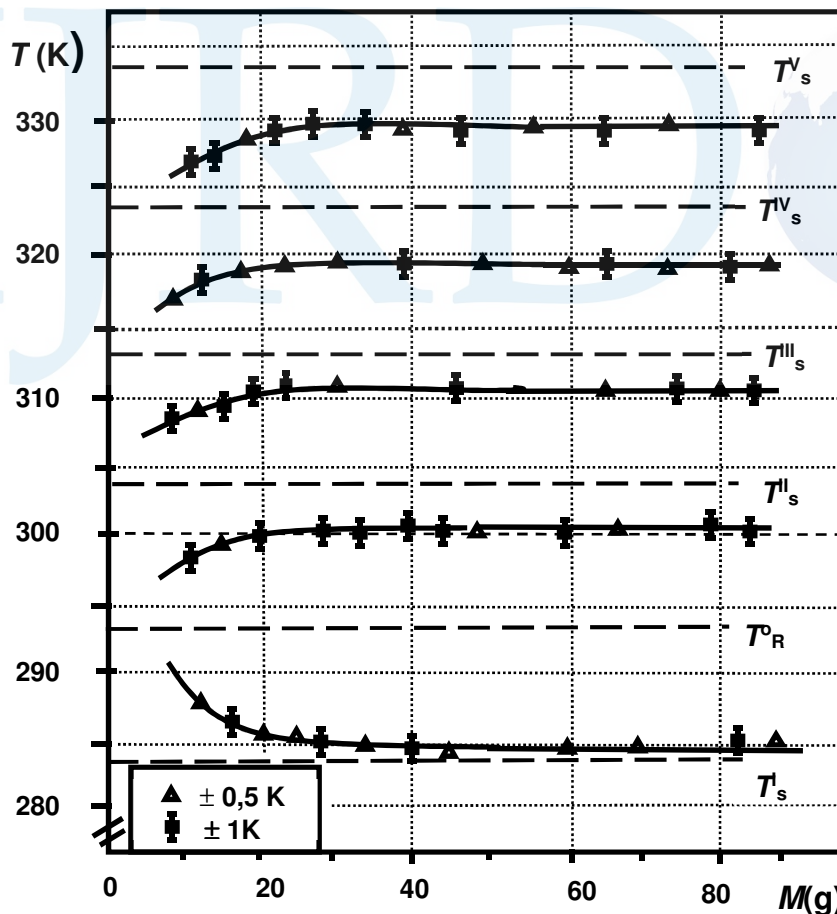
may be attained as close as possible. These facts are attempted to be elucidated in the proposed experiment.

3.-EXPERIMENTAL PROCEDURE.

3.1.-Experimental setup

The experimental apparatus is shown in figure 2. A set of two kind of commercial and 'humble' alcohol glass-thermometers –which are being displaced by 'black boxes' electronical ones-, of different accuracy, are consecutively employed to make temperature measurements. A first subset consists of four identical thermometers, with an accuracy of ± 1 K; the second one is also provided with four ethilic alcohol thermometers, but with an accuracy of $\pm 0,5$ K. Two kinds of measurements are proposed: firstly, we are interested in determining simultaneously the temperature for a set of subsystems S_i , obtained from the same reference matrix system –MS: Figure 2-.These measurements enable us to determine the influence of the relative size between the thermometric system and the reference matrix system.

FIGURE 3: Temperature of the respective subsystem versus the amount of water-



On the other hand, for some witness system, relaxation times while reaching the temperature of the laboratory are also measured; in this way, we can estimate the degree of technical isolation (insert of figure 2).

3.2.-Temperature measurements

We assume that the whole laboratory room -the universe- has a constant reference temperature T^0_R during the experiments. (Small fluctuations are always lower, or of the same order, than the accuracy of thermometers; and this can also be estimated). The reference matrix system that we want to measure is water (at an initial temperature of T^x_M); where the superscript x denotes the respective values of temperature $-T_M-$ selected, tending gradually towards T^0_R), for which a set of increasing amounts are quickly distributed sequentially into four vessels, previously rinsed out with a part of the same water. Immediately, each thermometer is introduced into the vessels containing a given amount of water M_j . In this way, we obtain a set of measured values $T_M \equiv \{T^x_{ij}\}$, where, $i=1,2$, denotes the different kind of thermometers, and $j=1,2,3,4$, the different amounts of water for each subsystem chosen.

3.3.-Time dependence of measurements.

The evolution of temperature with time is determined by selecting a witness for each set of measurements, made for both systems employed: a vessel and a thermometer. Thus we obtain two sets of values $T^x_V(t)$ and $T^x_T(t)$ respectively, which reach room temperature T^0_R at a finite time. These experiments also allow us to do further measurements with thermometers which start from the same temperature reference of the laboratory room.

It is evident that both kind of measurements must be carefully carried out; therefore, the degree of complexity of the experiment for the students may be greater than expected. For the sake of simplicity, only a set of measurements for each group is required; in this way, a closer collaboration among different groups is needed. This fact is a rather good deal that enables us to emphasize discussions among students, work programming, etc., being really all-suitable task (Larsson, 2017; Meltzer, 2004). Results obtained from the work of three groups of students are summarized and discussed in the next section.

4.-RESULTS AND DISCUSSION.

4.1.-Temperature measurements

Student worked in pairs. This group, taking approximately two hours, easily performs each first experience. Three groups of students make up measurements independently, selecting four points for each curve. Data analysis and representation is performed in a second session where results of the three groups are summarized. The obtained information is shown in figure 3, where, for each subsystem, the reading temperature T_M versus the respective amount of water M_j is represented. Dashed lines show the temperature for each matrix system: 283, 303, 313 and 323 K respectively, being $T^0_R=293$ K the reference temperature of the laboratory room.

Analyzing the curves, three main conclusions can be obtained:

i/The smaller the amount of water, the greater the disagreement of the measured values with respect to the referential ones (Note that the slope for the first curve -283 K- is opposed to the other

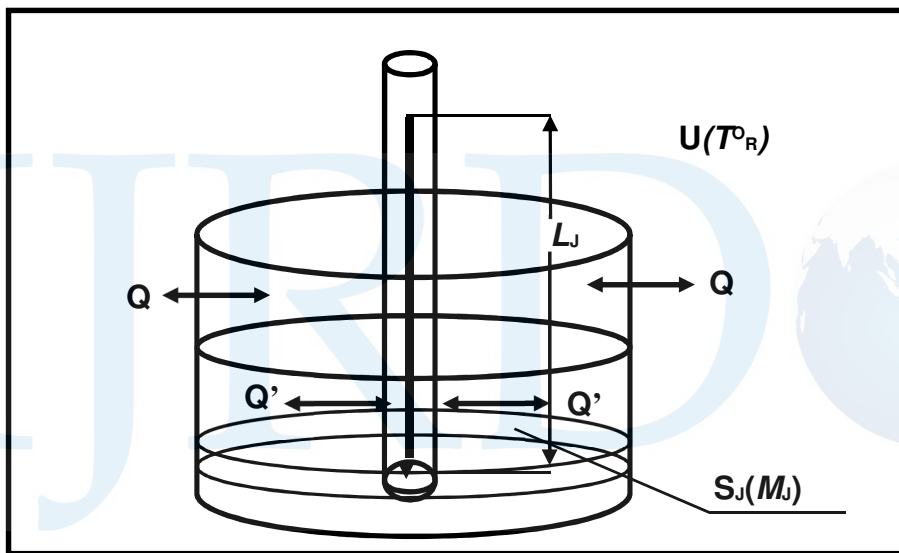
ones; this is because the actual temperature of this matrix system is lower than room's temperature, as it is explained below). For a quantity of water beyond 40g all curves show an asymptotic behavior.

ii/ These asymptotic values are different from the respective expected values T_s^x : the greater the temperature differences between the universe and the respective matrix systems, the greater this disagreement.

iii/It is worthwhile noticing that the accuracy of thermometers is not significant; thus, in the following, subscript I in T_{IJ} values is neglected.

An adequate theoretical model is now needed in order to explain the results obtained. In fact, bearing in mind that the response of thermometers is due to heat exchange between the systems involved, a close approach to these data can be obtained. This heat transfer is shown in figure 4.

FIGURE 4: Heat transfer between systems involved in the measurements



Firstly, if we assume an ideal thermal isolation of the measured systems with respect to the environment; i.e. the heat flow $Q' \gg Q$ –figure 4–, the energy balance, taken into account the first principle, may be rewritten as:

$$P_T S_T (L_J^x - L_o) + M_T C_T (T^x_I - T^o_R) = -M_J C_S (T^x_J - T^x_s) \tag{1}$$

where the first term on the left side is due to dilatation work of the thermometric liquid and the other two ones are the heat exchange of the thermometric liquid and the water respectively; P_T is the vapor pressure of the thermometric liquid; S_T , the section of the column; $L^x_J - L_o$, the dilatation length; M_T , and M_J are, the masses of the thermometric liquid and the systems respectively, and C_T , C_S their specific heat.

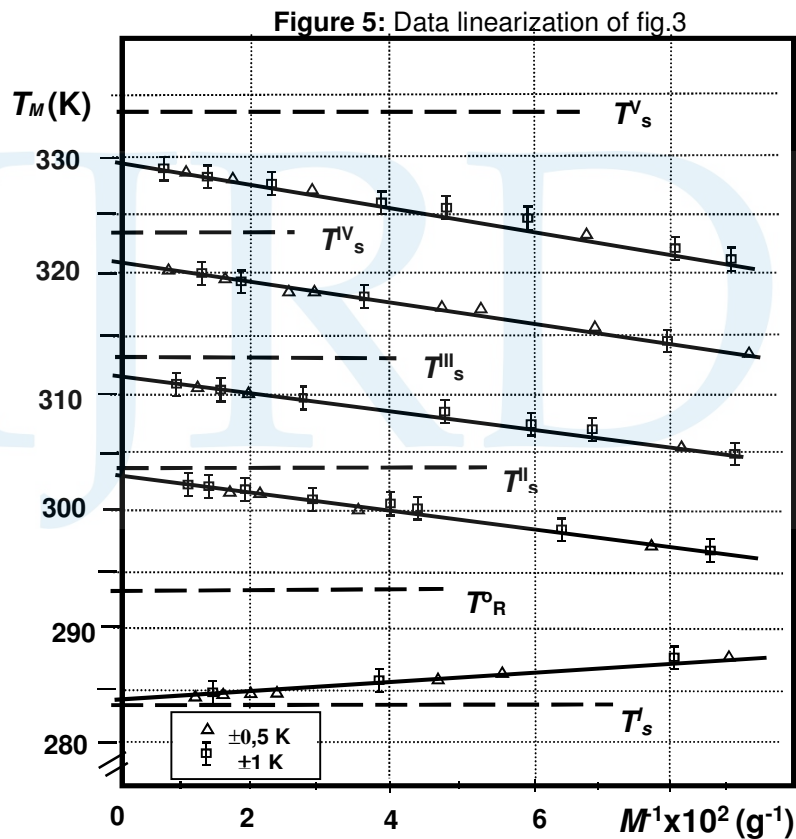
Taken into account that, in the linear region, length variation of the thermometric column is a linear function of temperature (Zemanski et al., 1997), it is possible to rewrite Eq.(1) as follows:

$$(B_T + C_T) M_T (T^x_I - T^o_R) = -M_J C_S (T^x_J - T^x_s) \tag{2}$$

where B_T is a given constant which depends on the intrinsic properties of the thermometric liquid and the cross-section of the column. Thus, (B_T+C_T) is a characteristic constant K_T of thermometers. For the sake of simplicity, due to the fact that, in this context, $T^x-T^0_R$ does not differ much from $T^x_s-T^0_R(=\Delta T^0_s$ in the following), Eq.(2) may be expressed as:

$$T^x_j = - \frac{M_T K_T}{C_S M_J} \Delta T^0_s + T^x_s \quad (3)$$

which indicates the measured values as a function of the involved parameters. Note that the slope of the curves is controlled by the sign of ΔT^0_s : the difference between the actual values of the matrix systems and the room temperature; thus, the former one with an actual value of 283 K -lower than the room temperature- is opposed to the rest, with actual values greater than 293K; in the first case, thermal contact implies that heat flows from the thermometer to the system as opposed to what happens in the others.



Equation (3) is in quite good agreement with the shape of the curves shown in figure 3. Accordingly, the real values of temperature T^x_s are displaced a quantity $\Delta T^x_j = T^x_j - T^x_s$ that depends, for a given thermometer, on the proximity between the temperature of the system and the room temperature (ΔT^0_s) and on the mass ratio of the respective systems involved in the measurements. A linearization of the curve of figure 3 is depicted in figure 5 showing us this dependence clearer. Thus, thermometric space is conical, rather than flat. This fact is shown in figure 6 and suggests some relationship to Minkowski space, which requires a deeper analysis that falls beyond the scope of this work. It is also represented in figure 6 the accuracy of both kind of thermometers employed; the size of the system will

them give the optimal accuracy of the thermometer and how it should be used. On the other hand, it is interesting to note a discrepancy in the ordinate origin for the curves of figure 5: it can be seen how these curves do not attain the respective expected values of T_s^x at the origin ordinate, when $M_j \rightarrow \infty$, [or $M_T \ll M_j$, when the system is great enough compared with thermometric size] the ideal condition at which the temperature of the system is not at all altered by measurement. The values of these discrepancies $-\delta T^x_0$ are shown in figure 7, where a linear dependence on ΔT^0_s is clear.

The curves of figure 6 are fitted to the following equation:

$$\Delta T^x_j = -\frac{M_T K_T}{C_s M_j} \Delta T^0_s - A(\Delta T^0_s) \tag{4}$$

instead of Eq. (3), where a new term is added $-A(\Delta T^0_s)$ in order to compute the origin ordinate, which, in the light of the results of figure 5, may be expressed as:

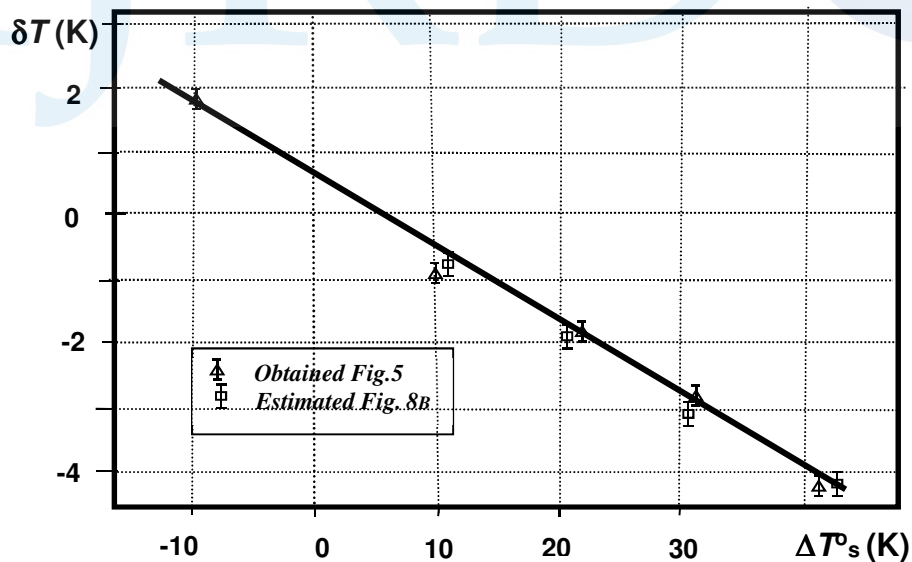
$$A(\Delta T^0_s) = D \Delta T^0_s \tag{5}$$

being D a given constant that it can be estimated as explained below.

4.2.- Time measurements

As it has been noted in previous paragraphs, flow heat from the system to the environment has been neglected. However, during the time of measurements, τ_m , and if these are not fast enough, this heat flow may be of interest. These facts may be evaluated by means of measurements of the relaxation time τ_R for a witness of both kinds of systems involved. Results are shown respectively in figures 8a and 8b.

FIGURE 6.-Asymptotic-deviation of data of fig.5 and fig 8b.



These are in good agreement with the well-known cool down law (Zemanski et al., 1997):

$$\Delta T(t) = \Delta T(0) \exp(-\alpha t) \tag{6}$$

where, for our case, $\Delta T(t) = T_s^x(t) - T^0_R$, $\Delta T(0) = T_s^x(0) - T^0_R (= \Delta T^0_s)$ and α is a given cold down constant which depends on the nature and geometry of the system. It is clear that $\alpha \rightarrow 0$ represents the ideal isolated

system, (our virtual condition), and $\alpha \rightarrow \infty$ the perfect thermal contact (instantaneous response, the best condition for a good thermometer). These virtual facts are shown in figure 9, where the linearization of the curves of figures 8 is represented as well. It can also be noted that the slope of the thermometer curves is higher than that of the vessels: a necessary condition, obviously.

Due to the fact that time measurements are close to one min., Eq. (6) can be linearized as:

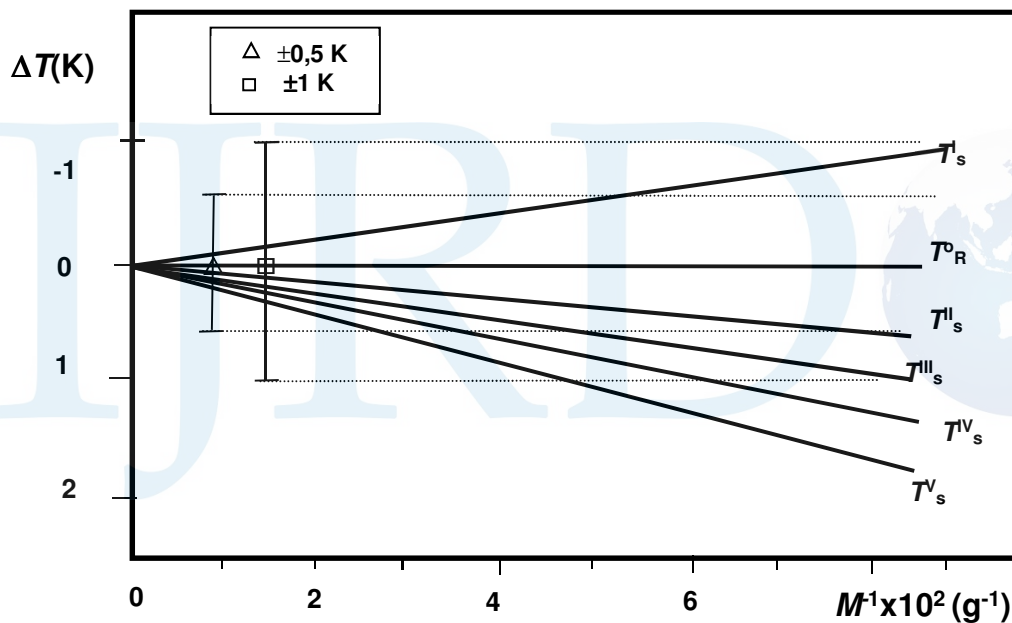
$$\Delta T(t) = \Delta T(0)(1 - \alpha t) \quad (7)$$

which enables us to interpret the factor of disagreement of Eq.(5). That is:

$$\Delta T(1) = -\alpha \Delta T(0) + \Delta T(0) \quad \text{or:} \quad \Delta T(1) - \Delta T(0) = -\alpha \Delta T^0_s \quad (8)$$

for a time of measurement close to one min. In this way, our results are satisfactorily explained. These values, so obtained from figure 8b, are also represented in figure 7.

FIGURE 7: 'Conical' thermometric space obtained from data of fig.5.



4.3.-Final remarks

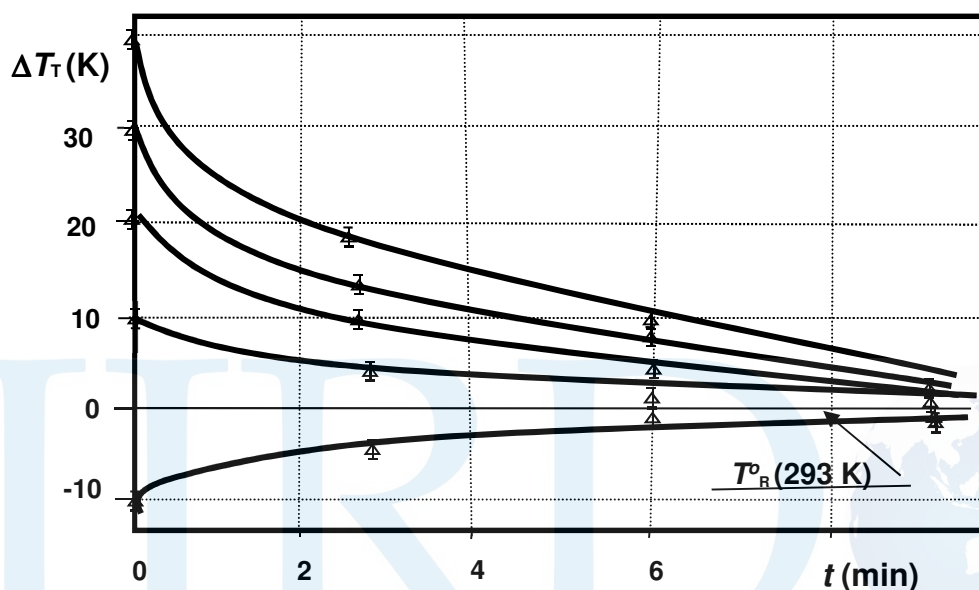
Some new experiments can be made by means of several simple improvements. For example, whether using thermocouples, for which the effect of the amount of water is now negligible, or by means of a better isolation of the vessels with thermo flasks, or both. However, it is interesting to note that the results obtained can be generalized for any thermometric system. The discrepancy between real values of temperature and the obtained ones, can be expressed in a generic way as:

$$\Delta T^X_j = -[K_T X(j) + C(\alpha)] \Delta T^0_s \quad (9)$$

where K_T is a given constant which includes intrinsic characteristics of the thermometric system, $X(j)$ is a dimensionless parameter that relates sizes of both kinds of systems involved, and $C(\alpha)$ evaluates the time response of both, thermometer and isolation systems.

Thus, for any thermometric system, the accuracy of the apparatus, relative size of the systems, thermal isolation, time measurements and intrinsic properties of thermometric system are correlated, and their influence must be evaluated by Eq.(9). Note also that, the nearer the initial reading of the thermometer to the temperature of the system, the greater the margin of precision. This is a trivial fact, anyhow, for any measurement process, however in this case it is not at all so clear. The historical difficulty for building thermometers and the complexity of the different scales of temperature can also be emphasized.

FIGURE 8A: Relaxation time for thermometers-

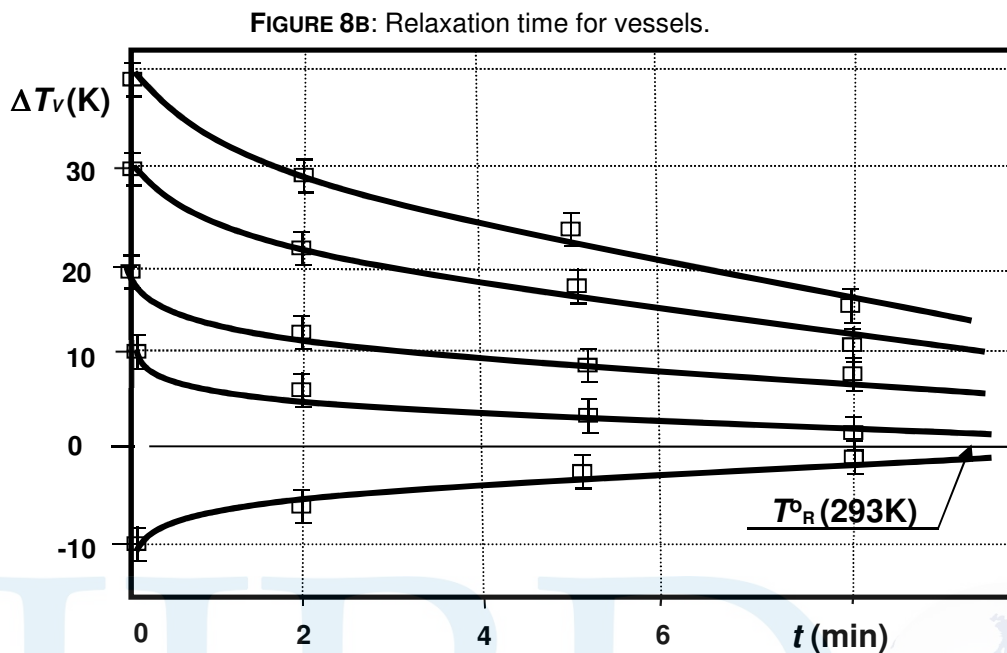


5.-STUDENTS' RESPONSE

Students enter introductory physics courses with strongly held misconceptions. One of them is the quite blind confidence on sophisticated apparatus, whether technical or mathematical ones. Before the experience, nearly all were limited to some familiarity with rather elementary calculus and equally elementary knowledge of thermal concepts, but they showed some ability to perform required manipulations. Only when they have the opportunity to handle materials themselves become curious and receptive. After the preceding experiment student should be in a position to recognize that (i) working within the confines of simple apparatus and techniques is rather fruitful; (ii) experimental work is really a laborious task that needs time: time to explore, to manipulate and to talk about meaning of facts and their interpretation. In more causal language, the students learn mainly after they have become confused, when they need to explain themselves about what's happened; when they must not follow a pre-established task and the deeper and complete analysis of the experiment arises on the way (Van Heulen, 1991; Tobochnik, 2017).

In fact, after the first session, they are really confused and misoriented. Only when data analysis is performed -in a second session- and some regularities arise, they showed an increasing interest. Thus, when results of the three groups were summarized, showing a clearer landscape, interactive discussions are promoted and they began to understand the firstly explained theoretical background.

They then propose new measurements, in order to improve doubtful data; instructors' help is quite only needed for the first session. It is important to show how these basic facts build up a deeper understanding of the subject (Wieman, 2015; Beals IV, 2017).



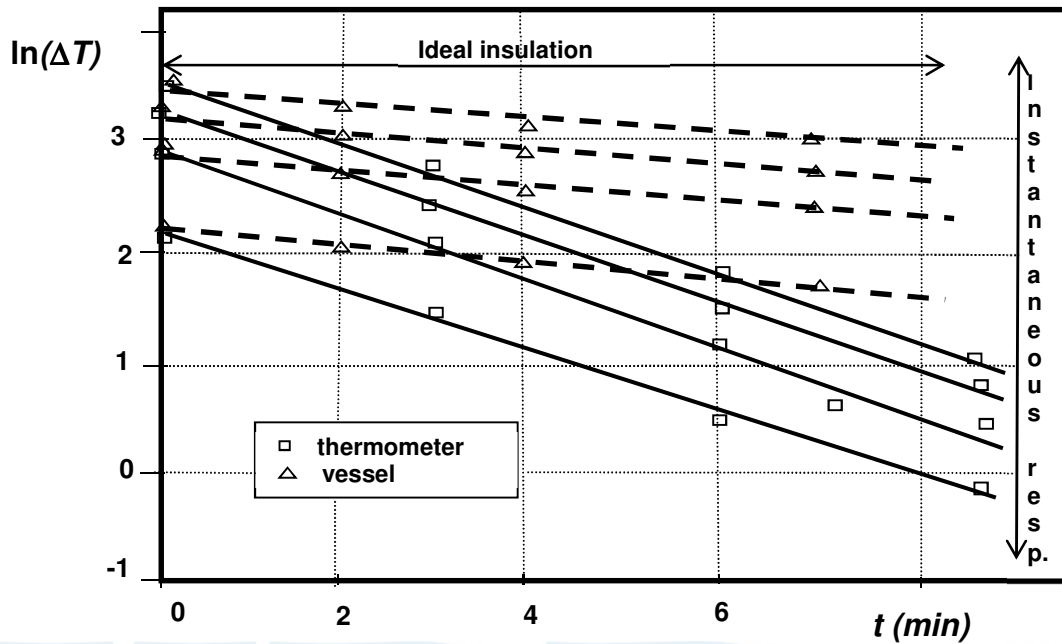
6.-CONCLUSIONS

In conclusion, this is a simple but laborious task, for introductory physics courses, because of the variety of subtle concepts involved and care manipulations required making it up correctly. Apart from the obvious economical advantages showed by the experiment, it also enables us to approach laboratory tasks in a more realistic way. In particular, operational processes in characterizing temperature as related to the accuracy of measurement are emphasized, as well as data analysis and further improvements are also pointed out.

It approaches also physical reality to everyday life, proposing, for instance, a similar home-work experiment with clinical thermometers -working in a limited range of temperatures but with better accuracy-, leading the students to a more realistic beliefs about physics procedures [8] and avoiding the strong confidence in the quite often sophisticated employed means.

On the other hand, these features lead to a meaningful discussion on the ideal concept of thermodynamic equilibrium, how it can be operationally reached, which are its limitations, etc..., a matter that is not generally discussed in elementary texts. This features can also easily extended to some others physical quantities which can complete the correspondence between mathematical postulations and physical reality: the operational definitions that are not taken currently into account in introductory physics courses, a necessary innovation in education research programs (MacDermott, 2001; Fraser et al., 2014).

FIGURE 9: Linearization of figs. 8.

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