Estimation of the temperature of starch particles-air flames

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Introduction

If the ability of reactive solid particles to give rise to combustible mixtures when they are finely dispersed in an oxidizing gas is well known since a long time, the actual mechanisms governing the propagation of combustion in this kind of reactive mixtures is far from being well understood. The reason for this is an insufficient knowledge of the fundamental properties of characteristic parameters of dust flames. To progress in the prediction of dust explosion hazards and of their effects, substantial fundamental results concerning the structure and properties of dust flames are needed.

Many works have been devoted to the measurement of the explosion pressure of dust air mixtures inside closed vessels and to try to derive the combustion rate from pressure evolution as function of time. In spite of the interest of this method of investigation, due to the simplicity of carrying out experiments, it does not permit to have a direct access to the measurement of the characteristic parameters of the reaction zone and to investigate its structure. As a result, several researchers[1,2,3,4] have undertaken the study of flame propagation in tubes. In previous papers, we have described an experimental method to study the propagation of a flame at constant pressure[5], displayed original results in the case of laminar starch particles-air flames[1], and discussed the possibility to derive the laminar burning velocity from the registration of the parameters of a freely propagating laminar flame[6]. However, despite the interest of these new results concerning the flame shape or fundamental parameters, such as the laminar burning velocity, the quenching distance,...the information to our disposal is yet insufficient to permit a correct description of a dust flame. Indeed, progression in this domain is dependent on the knowledge of another fundamental parameter of the flame which is the temperature. But, until now, we have only rough and contradictory results about the temperature of dust-air flames, as a result of the great difficulties to perform experiments of direct measurements of the temperature in this kind of reactive systems. We expose, hereafter, the first effort made to acquire new and original experimental results on this problem.

Experimental Method

Experimental setup

The method used to study the propagation of laminar dust flame at atmospheric pressure has been described in detail elsewhere[5]. Experiments are performed in vertical tubes. The suspension is produced at the bottom in a generator (see Fig.1) and flows in a laminar regime within the tube up to the top, which permits to fill the tube with a homogeneous suspension. At the time of ignition, the tube is open at the bottom end and

closed at the upper one. Ignition is achieved near the open bottom end by means of an electrically heated wire. As a result, a laminar flame propagates up to the closed end of the tube. Two different setups built on the same principle have been used, the first one (A, located at ENSMA) is 3-m long with a square cross section 0.20 x 0.2 m and the second one (B, located at INERIS) is 1-m long with a square cross section 0.1 x 0.1 m. Both are glass made, allowing visualization of flame propagation with cinematographic or video camera, and measurements by optical methods.

Temperature measurements

Two different methods have been used to measure the flame temperature: thermocouples and optical pyrometer.

Thermocouples

To get reliable results from thermocouple measurements, they have to be chosen so as to fulfill different requirements which may be difficult to satisfy in the same time: to be sensitive at low temperatures, support high temperatures (greater than 1000 K), have the shorter risetime possible, resist mechanically to the passing of the flame and the particles. For performing our experiments, we have used thermocouples specially designed at LED. They are made of 25µm-diam. chromel-alumel wires with a junction welding having a 25µm diameter, which gives them a 10ms risetime. The junction wires are coated inside thin refractory rods. These thermocouples can be mounted at different places along the tube; the junction is generally located in the centre of the cross section, but also near the walls. In some experiments, we have also used classical 200-µm chromel-alumel thermocouples. They have a better mechanical behavior, but their risetime is 200 ms.

Optical Pyrometer

We have used a pyrometric device based on the method of emission-absorption by the flame, which has been specially designed at LED for measuring the temperature of the solid phase in solid particles-gas mixtures. This apparatus has been described in detail elsewhere[7]. Its principle consists in processing three signals obtained by recording: (i) the emission of a reference source in the absence of the experimental medium, (ii) the self-emission of the medium, and (iii) the emission of the reference source through the experimental medium. The reference source is an infrared emitting diode. The originality of the apparatus consists in recording all signals by the same photomultiplier, that is along the same optical path (see Fig.1), and separating the different signals by modulating the emission of the source to distinguish the continuous part from the modulated one. The working wavelength of the device is 850 nm, the frequency of source modulation is 2 kHz, and the diameter of the zone explored in the flame is 3mm.

Flame characteristics

Our experiments have been performed in starch particles-air mixtures. The particles had a 20-μm mean diameter and their concentration in the mixture varied in the range 0-250 g/m^3, that is, for lean or stoichiometric mixtures. An example of a typical laminar starch-air flame propagating in the tube A is shown in Fig.2. In our previous works[5,6], we have displayed the dependence of the laminar burning velocity S_u on the mass concentration σ of particles and shown that the value of S_u was maximum around the stoichiometry. But it appeared that the value of S_u was slightly influenced by the size of the cross section of the tube: in the tube A, the maximum value of S_u is 0.27 ± 0.05 m/s, whereas it is only 0.22 ± 0.05 m/s in the tube B. With the same starch particles and with an experimental device close to ours, but with a cross section of only 0.05 m x 0.05 m, Mazurkiewicz and Jarozinski[8] derived a value of S_u of only 0.12-0.15 m/s. This indicates that flame propagation is influenced by the presence of tube walls and let us suppose that the dimensions of the larger tube (A) may be hardly sufficient to minimize the effects of lateral losses to the walls. The dependence of quenching distance on the concentration of particles has been also studied in tube A. It has been shown that the quenching distance was minimum around the stoichiometry and equal to 7 mm. Those measurements have permitted us to estimate that the lower flammability limit is obtained for a particle concentration σ=70g/m^3 and that the flame thickness could be of the order of magnitude of 3-4mm.

Results of temperature measurements

A typical example of the signal recorded with a 25-μm thermocouple in the tube A is shown in Fig.3. After a sharp increase of the signal at the passing of the flame front, the maximum value is reached within one hundred microseconds. Then, the signal decreases slowly and presents a lot of fluctuations. It is interesting to compare the signal delivered by a 25-μm thermocouple with a that delivered by a 200-μm one as shown by Fig.4: There exists an important difference in the first part of the signal as a result of the difference in risetimes. But later, the two signals display the same evolution as function of time: particularly, it can be observed that temperature maintains with large fluctuations at a high level during an important time interval (several hundred of microseconds). We have plotted in Fig.5 the value of the maximum temperature as function of mass particle concentration measured in the tube A. One can observe that the maximum is reached around the stoichiometric concentration. The results of temperature measurements made with 25-μm thermocouples in tube B reveal (see Fig.6) that, for lean mixtures, there are no significant differences in the values of the maximum temperature recorded in the

middle of the cross section of the tube B in comparison with the results of tube A. Moreover, measurements made with the thermocouple located at 3 cm from the wall, thus recording the temperature evolution along the side of the flame, leads to maximum values of the temperature very close to that recorded at the flame tip (see Fig.7).

With the optical pyrometer, a first series of experiments has been done for lean mixtures, at particle concentration around σ=150g/m^3. Typical signals delivered by the pyrometer are shown in Fig.8: signals (a) and (b) represent solid particles temperature and absorption coefficient evolution, respectively. Before the arrival of the flame, the temperature signal has a constant value corresponding to the threshold of the sensitivity of the apparatus. On the passing of the flame, it increases whereas in the same time the absorption coefficient sharply decreases. Maximum of temperature is reached simultaneously with minimum of absorption coefficient, within about 200 ms. The value of this maximum temperature is around 1300K. Then, the temperature decreases and returns to its initial value after about 2s. The absorption coefficient ensues the opposite behavior, re-increasing to reach a constant value.

Discussion

Comparison of the values of maximum temperature measured by means of thermocouples, with the thermodynamic values of the temperature of the adiabatic flame displays a deficit of several hundred degrees of the measured values, up to 500 K for stoichiometric concentrations (see Fig.6). A temperature deficit of the same order of magnitude had already been observed by Smoot and Horton[9] in the study of laminar flames propagating in pulverized coal dust-air mixtures. We have verified that the correction due to radiative heat losses by thermocouples is inadequate to explain this discrepancy. With the pyrometer, the gap between experimental and theoretical values is reduced, but remains however significant (about 200 K). The difference between the values indicated by the two methods for measuring the temperature may come from the working principle different for the two apparatuses: the thermocouple indicates the temperature of gases, whereas the pyrometer indicates that of particles. Anyway, it is legitimate to suppose that this temperature deficit should not be attributed to the method of temperature measuring, but to the phenomenon itself.

The 25-µm thermocouple records show also that the maximum temperature is reached about 100 ms behind the flame front. As a result of their too long risetime, the 200-µm thermocouple are inappropriate for determining the maximum temperature. The time (300-400 ms) during which temperature maintains at a high level with, however, important fluctuations, is consistent with the existence of packets of dust burning with a delay behind the main flame front, as attested by photographs. The fact that the

temperature measured at the rim of the flame is quite the same as that measured at its tip indicates that the lateral losses should be unimportant at the scale of the flame. As regarding the maximum temperatures recorded in the larger and the smaller tube, it appears that the differences in the values of S_u noticed previously between the two apparatuses, should not be attributed to problem of adiabaticity, but rather to mechanical effects of boundary layer.

In pyrometric records, the maximum of temperature is reached later than in thermocouple measurements. This is probably due to the fact that the temperature delivered by the pyrometer is a value integrated over the cross section of the tube. As shown by photographs, the shape of the flame is elongated with important curvature of the front: thus the maximum temperature is obtained when the cross section surface of the flame has reached its maximum, which is achieved about 200ms behind the flame tip. The substantial decrease of the absorption coefficient at the rear of the flame front indicates that, at the considered concentrations, the medium becomes nearly transparent during combustion, which is an additional confirmation that, for starch particles-air mixtures, combustion occurs in gaseous phase. The duration of the zone with low value of absorption coefficient is consistent with the length of the flame plume observed on the photographic records (Fig.2). The re-increase of the absorption coefficient behind this zone is likely to be due to the turbulent mixing of the unburnt particles with gases, which generates again a suspension having optical properties of a semi-transparent medium.

Finally, the more plausible explanation of temperature deficit seems to be the heat loss due to flame radiation toward the burnt products at the rear of the front. Nevertheless, this hypothesis requires further examination.

Conclusions

The temperature of a starch particles-air flame freely propagating in tubes has been measured by means of short risetime thermocouples in two different setup and with an optical pyrometer in the larger tube. It seems to be confirmed that there exist a deficit of the measured temperature values in comparison to the theoretical value of the adiabatic flame temperature, despite this deficit is less important in pyrometric measurements than in those obtained with thermocouples. Our results diverge from those of Mazurkiewicz and Jarozinski[8] who have obtained in the same mixture values greater than ours. However, their results are questionable since in the same time, those authors display a dependence of the laminar burning velocity on the particle concentration which presents around the stoichiometry a behavior opposite to that expected. Finally, it appears of great interest to go on in improving experimental methods for measuring the temperature of heterogeneous solid particles-gas mixtures. There exists yet a great uncertainty in the

knowledge of the temperature of flames of this kind, and further information is needed about the heat transfer processes inside and outside of the flame.

Additional experimental results will be shown at the moment of presentation.

References

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Figures

Fig.1 Experimental setup

Fig.2 Sequence of propagation of a laminar flame in a starch particles-air suspension (mass particle concentration σ=120 g/m3)

Fig.3 Example of thermocouple signal in a laminar starch particles-air mixture

Fig.4 Comparison of the signals recorded by a 25-μm (a) and a 200-μm thermocouple (b).

Fig.5 Variation of the maximum temperature behind the flame front recorded by the thermocouple, as function of the mass particle concentration in the tube A.

Fig.6 Comparison of the temperatures recorded by thermocouples ● in tube A and o in tube B, with the theoretical values of the adiabatic flame temperature ----

Fig.7 Variation of the maximum temperature behind the flame front recorded by the thermocouple, as function of the mass particle concentration in the tubeB.
o at the tip of the flame; ● at the rim of the flame.

Fig.8 Typical signals delivered by the optical pyrometer in a starch particles-air flame (a) temperature, (b) absorption coefficient.

Fig 2

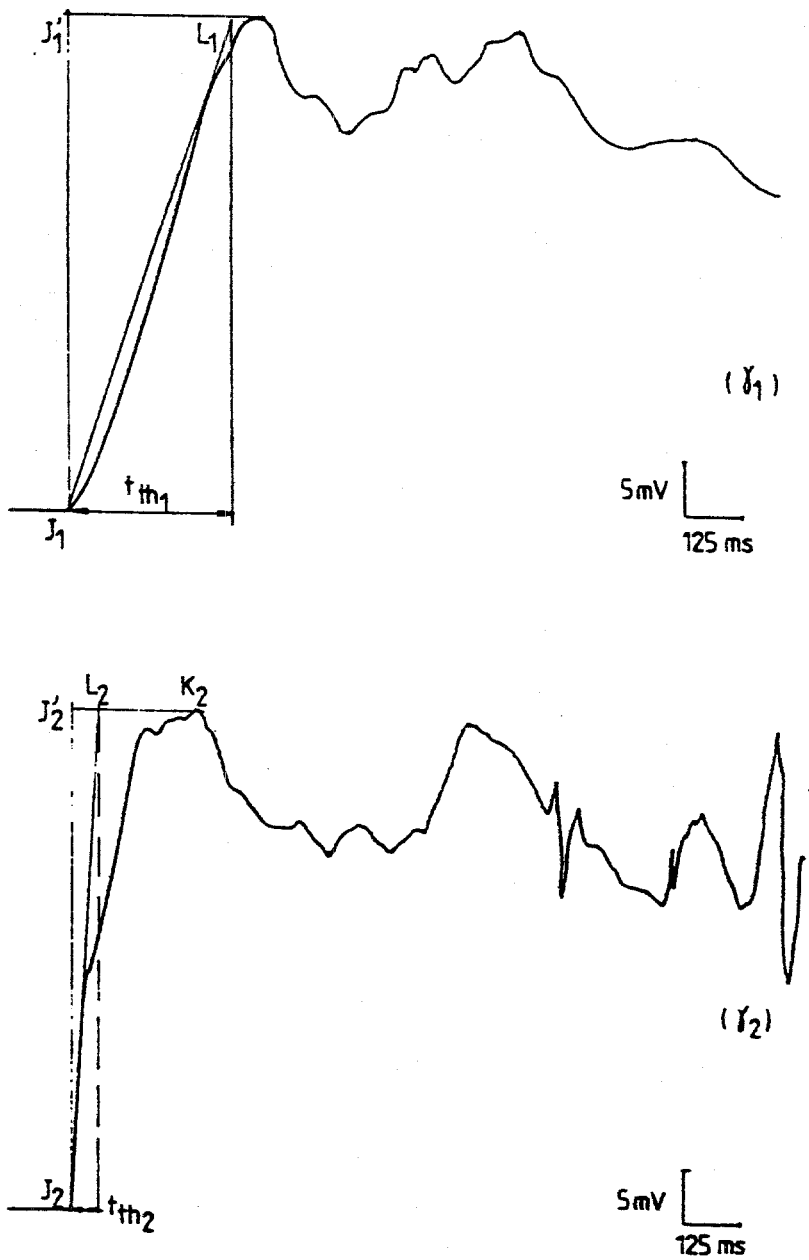

(b)
J'_1
L_1
t_{th_1}
J_1
(γ_1)
5mV
125 ms
(a)
L_2
K_2
J'_2
J_2
t_{th_2}
(γ_2)
5mV
125 ms

Fig 4

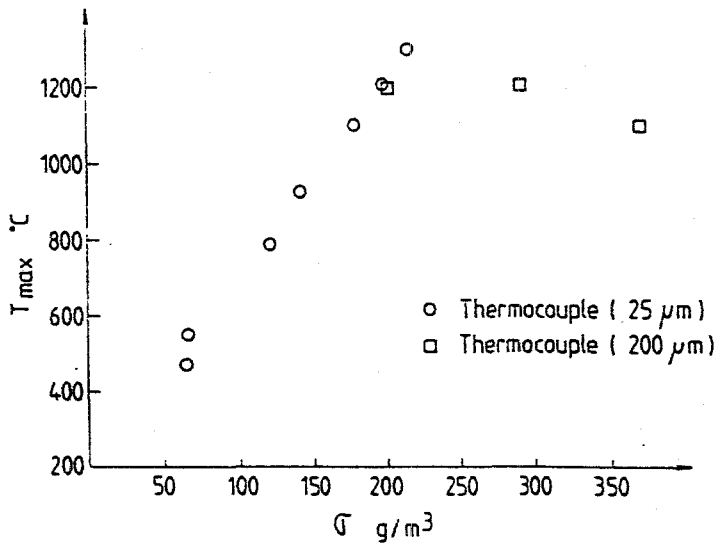
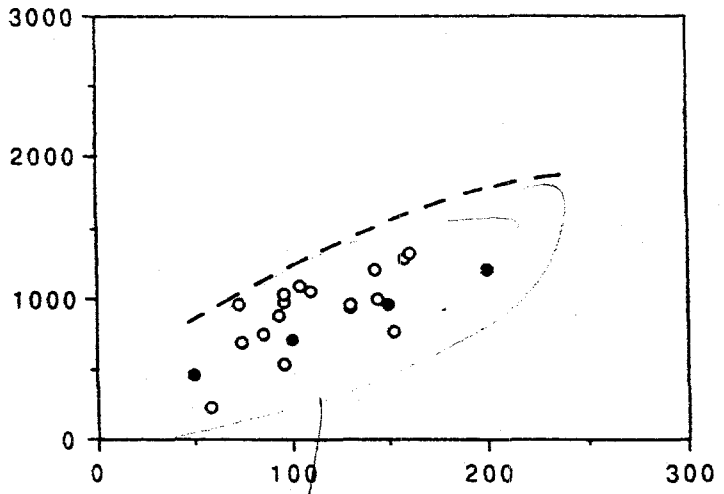

T max °C
1200
1000
800
600
400
200
50
100
150
200
250
300
350
σ g/m3
Thermocouple (25 μm)
Thermocouple (200 μm)

Fig 5



n'y a-t-il pas lieu de s'interroger sur la dispersion
avec semblable des résultats ?

Fig 6

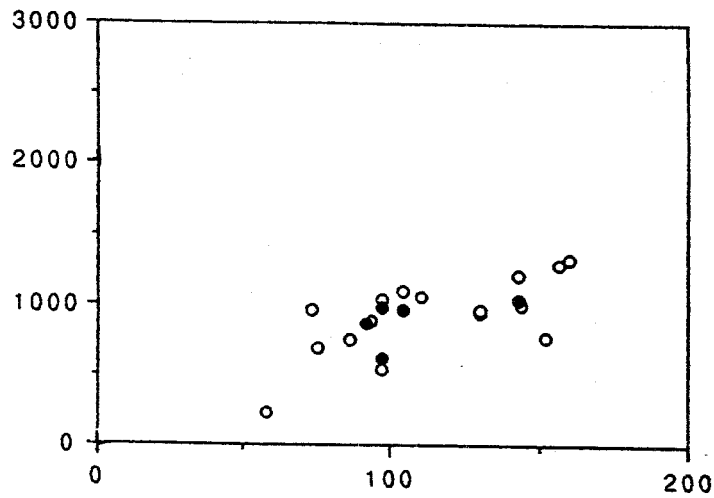
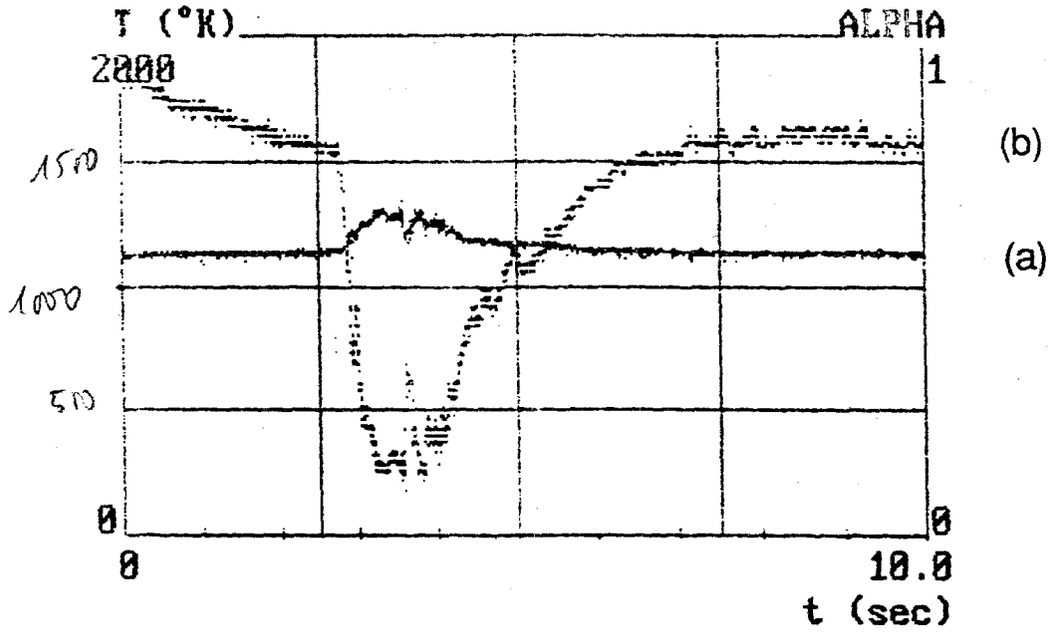


Fig 7



comprends pas bien l'échelle de température. Est-ce à dire qu'au temps 0 la température de particules est de 1100°K ?

Fig 8

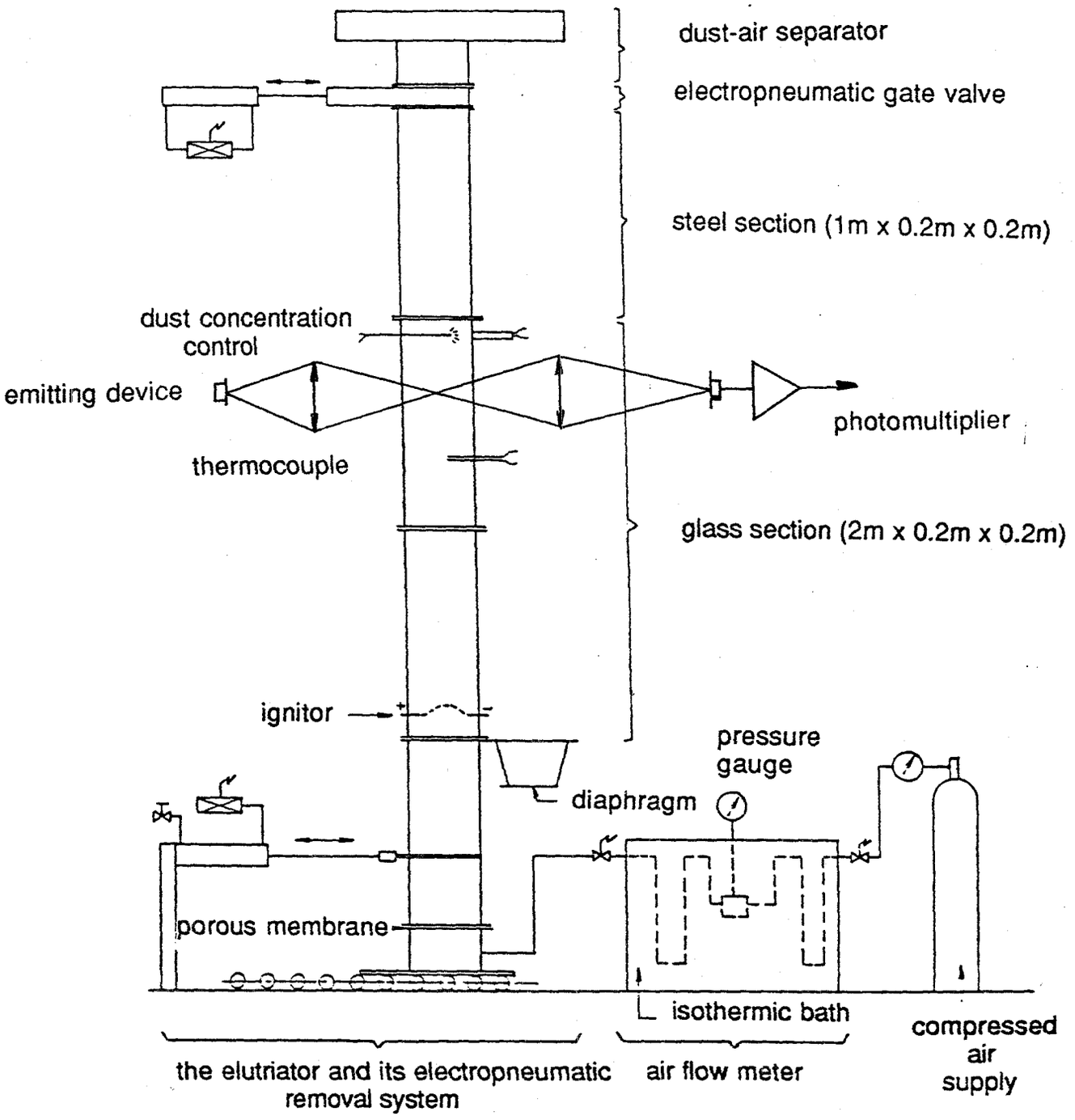

dust-air separator
electropneumatic gate valve
steel section (1m x 0.2m x 0.2m)
dust concentration control
emitting device
photomultiplier
thermocouple
glass section (2m x 0.2m x 0.2m)
ignitor
pressure gauge
diaphragm
porous membrane
isothermic bath
compressed air supply
the elutriator and its electropneumatic removal system
air flow meter

Fig 1