INTERACTION BETWEEN TEMPERATURES, AIRFLOW AND CHIMNEY DESIGN IN INDIRECT FREE CONVECTIVE SOLAR DRYERS

Michael W. Bassey Ph.D.
International Development Research Centre
B.P. 11007 CD Annexe, Dakar, Senegal

ABSTRACT

Solar dryers have so far not attained any significant level of utilization in Africa due to factors ranging from lack of knowledge of their existence to cost. The problem of cost is related to the fact that the technology, although simple in operation, requires materials which are not usually available locally. Farmers cannot also afford to use fans for moving the air through the dryers. On the other hand, dryers which use free convection for circulating the air have significant design problems which cause low airflows per unit collector surface area, making them uneconomical for drying operation.

This paper presents and discusses a wide range of experimental results, obtained using two indirect free convective solar dryers under no-load and loaded conditions using rice, under typical conditions existing in Sierra Leone. One of the dryers had a single passage in the air heater whereas the other had a double passage air heater. Five different chimney configurations were used on the dryers and temperatures were recorded at various positions in the dryers, over a period of three years.

Based on the available data, explanations are presented for the relative performance of the two dryers under various conditions. The interaction between, temperatures in the drying chambers and the chimneys, solar radiation, cloud and airflow rates are discussed. It is generally noted that the relationship between parameters is complex. However it is possible to compare dryers using mean daily chamber temperatures and mean daily solar radiation intensities. Results indicate that a short chimney (about 50 cm) painted black and covered with a transparent material could be more desirable. In addition, single air passage heaters are considered more appropriate for use with free convective solar dryers. Finally, the results presented can be used for further modelling work on these dryers.

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1. INTRODUCTION

1.1. Background

The use of solar dryers in rural areas of Africa has been severely restricted due to the low air flow rates existing in natural convection dryers. Due to the low income of farmers and the absence of electricity, dryers for rural applications generally do not have a mechanical means, such as a fan, to circulate warm air through the crops.

This restriction in the design of solar crop dryers has therefore posed a great challenge to researchers engaged in solar dryer design. Because of the difficulties in obtaining a design which circulates air only by free convection, many researchers have concluded that these dryers do not have a place in crop drying.

However, since forced flow solar dryers will in the foreseeable future be out of the reach of most rural African farmers, efforts must be made to obtain satisfactory airflows in free convection dryers. This can be achieved by systematic investigations into the operation of these dryers under real life or simulated conditions. Although many dyrers have been discussed in the literature, e.g. Brace Research Institute (1975) and Exell (1980), the author is unaware of published work which have attempted to study and explain the interaction between dryer design, ambient conditions and airflow. Bassey (1982 (a)) has described the effect of various chimney designs on the temperatures obtained in an indirect solar dryer using an air heater with two air inlet channels. The study showed that it may not under all ambient conditions be useful to have tall chimneys on free-convective dryers. Furthermore, results indicated that the chimneys in these dryers should be designed so as to minimize heat losses from them.

1.2. Aim of Paper

The purpose of this paper is to present results of a study aimed at describing the complex response of indirect free-convective dryers to their environment. It is hoped that this work, which is intended to highlight areas for further studies, will generate interest in the development and study of methods (and their related mechanisms) for improving airflow in free convective dryers.

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Two dryers were studied experimentally using five chimney configurations. One of the dryers had an air heater with a single air passage between the transparent glass cover and the absorber plate. The other dryer had two air passages; one above and the other below the absorber plate. Measurements of temperatures were made throughout the dryers under various ambient conditions existing in Sierra Leone, under no-load and loaded conditions using rice.

2. EXPERIMENTAL APPARATUS

2.1. Description of Solar Dryers

Two dryers were used in this study and each consisted of three main parts: the air heater; the drying chamber; and the chimney. The difference between both dryers existed in the design of their air heaters. Figs. 1 and 2 show general front and side views respectively of the dryers.

The air heaters for both dryers were made from 1.2 cm plywood, 0.16 cm galvanized iron sheet, 0.3 cm thick glass, and 10 cm thick fibreglass wool as insulation. Dryer I had a single air passage (4 cm high and 70 cm wide) between the absorber plate and the glass cover as shown in Fig. 3. In dryer II, shown in Fig. 4, the two air passages (both 70 cm wide) are separated by the absorber plate. The heights of the top and bottom passages are 4 and 2 cm respectively. The glass covers are approximately 90 cm by 90 cm in surface area and are attached to the solar collectors using wood putty.

Both drying chambers for the dryers are identical, measuring 90x90x90 cm3 and are made from 1.27 cm thick plywood. They have openings at the top and the sides for loading and unloading.

The air heaters are connected to the drying chambers by means of a rectangular channel equal in cross sectional area to those of the air passages. Both dryers are mounted such that the air heaters are inclined facing south at an angle of about 20 degrees to the horizontal.

2.2. Chimney Configurations Used

In order to assess the effects of using different chimneys on the dryers, provision was made for changing the chimneys during tests. In addition to using chimneys of various heights and color, an innovation used was to make one of the chimneys a solar collector.

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The different types of chimney used were made of 0.16 cm galvanized iron sheet and each had an internal diameter of 15 cm. Their special features were:

(a) 38 cm high, unpainted;
(b) 38 cm high, painted black outside;
(c) 38 cm high, painted black outside, surrounded by transparent plastic;
(d) 180 cm high, painted black;
(e) 180 cm high, painted black outside, surrounded by transparent plastic.

The chimneys using a transparent cover had an air gap of 2 cm between the blackened outer wall and the plastic material, care being taken during construction to ensure that the plastic did not touch the chimney walls during operation.

2.3. Instumentation

Temperatures were measured at several positions on dryers I and II as shown in Figs. 5 and 6, using copper constantan thermocouples connected to a ten-point Thermo Electric Temperature indicator or a portable "Digimite" indicator. Both equipment were accurate to 0.5 °C.

Total solar radiation on a horizontal surface was measured using an Epply precision spectral pyranometer connected to an electronic integrator and printer. The output in units of Wh/m2 was recorded at 10 minute intervals.

Wind speeds were monitored during the experiments using a hand held cup anenometer.

3. EXPERIMENTAL PROCEDURE

3.1. Tests Under No-load

Chimneys were attached to the dryers and with the collectors facing south, measurements were made of the temperatures at the locations shown in Figs. 5 and 6. Total solar radiation on a horizontal surface, wind conditions and other ambient conditions were noted during each experiment which took place between 0800 and 1600 hrs.

Tests carried out to compare the effects of the air heater design used similar chimneys on both dryers I and II. During other tests, various chimneys were attached.

to the dryers. Each experiment was repeated over several days, over a period of three years.

3.2. Tests Under Load Using Rice

Two sets of experiments were carried out with the dryers under load. The first tests consisted of making measurements in the dryers for rice beds 2.5, 5.0, 7.5 and 10 cm high. The rice was supported on a single tray in each dryer, situated above the inlet into the drying chamber. During these tests, the chimneys used were both 38 cm high and unpainted.

The second set of tests under load were done using similar bed depths as above. However dryers I and II had chimneys 38 and 180 cm high respectively, both being painted black and covered with a transparent plastic cover.

For each bed of rice dried, drying was carried out over a period of days to reduce its moisture content to the required value.

4. RESULTS AND DISCUSSION

4.1. Relative Magnitudes of Temperatures in Dryers Under No-load

Typical results for the dryers indicate that plate temperatures are the highest. For dryer I, these temperatures range between 80 to 100 °C, depending on the solar radiation. In the case of dryer II, the temperature at the top of the plate are generally lower than those of dryer I. Differences between the temperatures on both sides of the absorber plate for dryer II are about 40 °C.

Temperatures in the drying chambers are less than 50 percent of the plate temperatures as a result of the low flow-rates through the air heaters.

4.2. Influence of Solar Radiation Under No-load

During all experiments, total solar radiation was measured and recorded every 10 minutes. Solar radiation intensities were then evaluated from these readings. In addition, mean values of intensity of solar radiation for a whole day were estimated by dividing the total energy for that day by the period of the test.

The dependence of the temperatures in the dryer on the available solar energy is important in assessing dryer performance. Figs. 7 and 8 show the variation of

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temperatures in the dryer with time, for various mean intensity of radiation, over the period of the experiments. Results are presented for the various chimneys used.

As would be expected, the chamber temperatures are generally higher for higher availability of solar radiation. It is however important to note that even though the mean solar intensities are quite different for each comparison shown, the chamber temperatures for lower mean intensities are at times very close to or greater than temperatures for higher intensities. This behaviour can be related to the variation of solar radiation during the experiments. It was observed that during cloudy conditions the chamber temperatures could be significantly lowered as shown e.g. in Fig. 8 (C).

All the results presented in Figs. 7 and 8 show that the temperatures in the chambers are for both dryers between 30 and 50 °C, indicating the potential usefulness of indirect free-convective solar dryers.

In practical applications, it is useful to know the magnitudes of temperatures to be expected under different solar radiation conditions as it enables the dryers to be satisfactorily designed. A parameter which could be used to correlate the chamber temperatures is the mean daily solar radiation intensity on a horizontal surface, noting that this gross value does not take into account the intermittent nature of solar radiation. Results for dryer II have been presented and discussed by Bassey (1982 (a)) but will be reproduced for comparison with results for dryer I.

The variation of daily mean chamber temperatures with mean solar radiation intensity for all the chimney configurations studied are shown in Figs. 9 and 10, for dryers I and II respectively. Some scatter are noted in the data which are a result of the influence of the intermittency of the available solar energy due to cloud cover. It is possible to have the same mean solar intensity on two days although the mean temperatures for those days may be different.

A close study of the results in Fig. 9 indicates that the data can be represented by straight lines as shown. Similar observations are made in Fig. 10 for dryer II.

4.3. Effect of Type of Chimney Used Under No-load

Results in Figs. 9 and 10 show an influence of chimney configuration on chamber temperatures under no-load. A detailed discussion of these results for dryer II

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have been given by Bassey (1982(a)). It was pointed out that for dryer II temperatures are decreased when the 38 cm chimney is painted black and then covered with the transparent cover. Increasing the length of the chimney tends to increase the chamber temperatures.

In the case for dryer I the temperatures are increased when the chimney is painted black and then covered with plastic (see a typical result in Fig. 11). Increasing the height of the chimney decreases the temperatures in the chamber.

These results can be explained by the flows through the dryers as a result of the interaction of the chimney design, the air heater and the surroundings.

Let us consider the case when the 38 cm tall chimney is attached to dryer I under no load. A chamber temperature is obtained as a result of ambient air being heated as it passes through the single channel heater. If the chimney is painted black, it is now heated by solar radiation causing a slightly higher flow rate through the air heater. As a results the chamber temperatures are increased. Furthermore if the blackened chimney is covered with a transparent cover, the heat losses from the chimney are minimized, resulting in higher temperatures inside it, this in turn causing higher buoyancy forces which increase the air flow. Again, temperatures are obtained as shown in fig. 9. Increasing the height of the chimney tends to increase heat losses from it which in turn decreases the flow rates: the temperatures in the drying chamber are thus lowered.

Similar arguments have been given elsewhere Bassey (1982(a)) for the behavior of dryer II with respect to the various chimneys in Fig. 10 and will therefore not be repeated here. Nevertheless it is noted that the converse behavior exists as a result of the extra cooler air being introduced through the bottom channel.

It is easily seen from the above that even though reasonable operating temperatures can be obtained in indirect free convective dryers, it is possible that airflow rates can be very inadequate as a result of chimney design. Many solar dryers have tall and at times black chimneys which may in fact decrease airflow rates depending on the prevalent ambient conditions such as the incidence and duration of clouds, wind, and ambient temperatures. For conditions existing in Sierra Leone, detailed examination of data (not shown here for lack of space) has consistently supported this argument.

This problem of the adverse effect of chimney design and the above explanations are further reinforced by considering the relative magnitudes of chimney and

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chamber temperatures. Although temperatures in the chimney are usually higher than those in the drying chamber, some conditions exist where this is not so, as shown by typical results in Fig. 12 for both dryers I and II.

Results for dryer I, for the 38 cm unpainted chimney at low solar radiation conditions (mean intensity of 485 W/m2), indicate generally lower chimney temperatures. For dryer II using the 180 cm chimney painted black under similar solar radiation intensities (469 W/m2), the chimney temperatures are significantly lower than those in the chamber during the whole day. An examination of the variation of solar radiation intensities during the day for the above type of results show relatively low levels of solar radiation, frequent and prolonged cloud cover, and either low ambient temperatures (depending on the season) or windy conditions.

4.4. Temperatures in chimney and Chamber Under Load

Rice at initial moisture contents ranging form 25 to 45 percent (dry basis), depending on the degree of soaking, was used during the on-load tests.

Based on earlier discussions, the relative magnitudes of temperatures in the chimney and drying chamber give an indication of airflow through the dryer. Fig. 13 shows chimney and chamber temperatures for two heights of the rice bed for dryer I. It is noted that the solar radiation conditions are very similar.

For the rice bed 2.5 cm high the chamber temperatures (below the rice bed) are higher than the chimney temperatures throughout most of the day. Earlier during the day, the chimney temperatures are higher. Results for the 7.5 cm rice bed shows very similar behaviors but the temperatures are relatively lower.

These data are consistent with the preceeding discussions under section 4.3. Increase in the height of the rice bed should reduce the flow and for the single channel air heater this implies a drop in temperatures in the chamber.

Results for prototype II shown in figure 14 also show temperatures consistent with the explanation given for the airflows through the two channel air heater, i.e. a reduction of airflow due to the deeper rice bed produces higher temperatures in the chamber (underneath the bed).

The substantially lower temperatures in the chimneys, compared to those in the drying chamber, further indicate the potential flow problems in free convective dryers. It is possible that these lower chimney temperatures, caused by the air being cooled by water from the crop, can substantially lower the flow rates. Adverse ambient conditions earlier discussed and poor chimney design can make such dryers very inefficient.

4.5. Comparison of Effects of Air Heater Design

The behavior of the dryers suggest that the design of the air heaters plays an important role. Also, it has been noticed that the chimney configuration also affects the dryers performance. Results in Fig. 15 gives an overall indication of the relative effects of the two air heaters on the performance of free convective dryers for various chimney configurations, under no-load.

For the unpainted 38 cm chimney and the 180 cm chimney with cover, the air heaters appear to give similar dryer temperatures. When the chimney is painted black and covered (Figs. 15 (b) and (c)) the single channel air heater gives higher chamber temperatures compared to the double channel heater. The 180 cm black chimney gives results contrary to those e.g. obtained in Fig. 15 (b) and (c). This particular data may be due to lower flow rates, caused by the tall chimney, decreasing temperatures in dryer I and increasing it in dryer II.

Under load, Fig. 16 shows that for the 5 and 10 cm deep rice beds, dryer I gives lower cabinet temperatures than dryer II although the former has higher plate temperatures.

4.6. Overall Significance of Results

The preceding discussion indicates that the flows through indirect free convective dryers are in real life governed by many complex parameters. Some of these are: the chimney design, the air heater design, the ambient temperature, cloud cover, available solar radiation and wind conditions.

Results suggest that in the design of these type of dryers the single channel air heater may be adequate considering its relative performance to the double channel heater. Furthermore, the use of tall black or unpainted chimneys are considered unsuitable under atmospheric conditions where cloudy cover, low solar radiation intensities and wind may exist. Under these conditions a 50 cm chimney painted black and covered with transparent plastic is recommended. However under clear sunny conditions, tall chimneys may prove to be more advantageous. Thus the overall design of free convective dryers are location specific.

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Another important implication of the results is that during drying, the temperature in the dryer above the crops is substantially lower than that underneath. Thus in the design of these dryers there should be a revision of the usual assumption of constant densities in the dryer to take into account density changes throughout its height. (This has been treated elsewhere, Bassey (1982 (b)). In order to do this, results such as those obtained in this study can be very useful.

In addition to the above comments, experience gained during the course of the study suggests that an experimental study aimed at assessing the effects of all the relevant parameters is very tedious. Specific aspects need to be scrutinized in future experimental activities. In order to understand the response of the dryers to various conditions a next step should be the mathematical modelling of free convective dryers using realistic inputs such as those reported in this paper. Such a strategy could rapidly identify areas for further experimentation leading to better dryer designs.

5. CONCLUSIONS

The following main conclusions can be drawn from this paper:

(a) The interaction of various parameters makes the study of indirect free convective dryers very complex. It is however possible to quantify their overall performance by relating mean daily temperatures in the drying chamber to mean daily intensities of radiation.

(b) In general, the type of chimney used affects the flow of air through the dryer. For cloudy, low solar radiation conditions existing in many tropical areas, it is advisable to use short chimneys (about 50 cm high) painted black and with a transparent cover around it. Taller chimneys may suffer substantial heat loss.

(c) Air heaters with a single air passage are considered more appropriate for use on free convective solar dryers due to their simplicity in design and generally higher temperatures.

(d) Results presented can be used as a basis for carrying out analytical modelling studies with a view to improving dryer performance.

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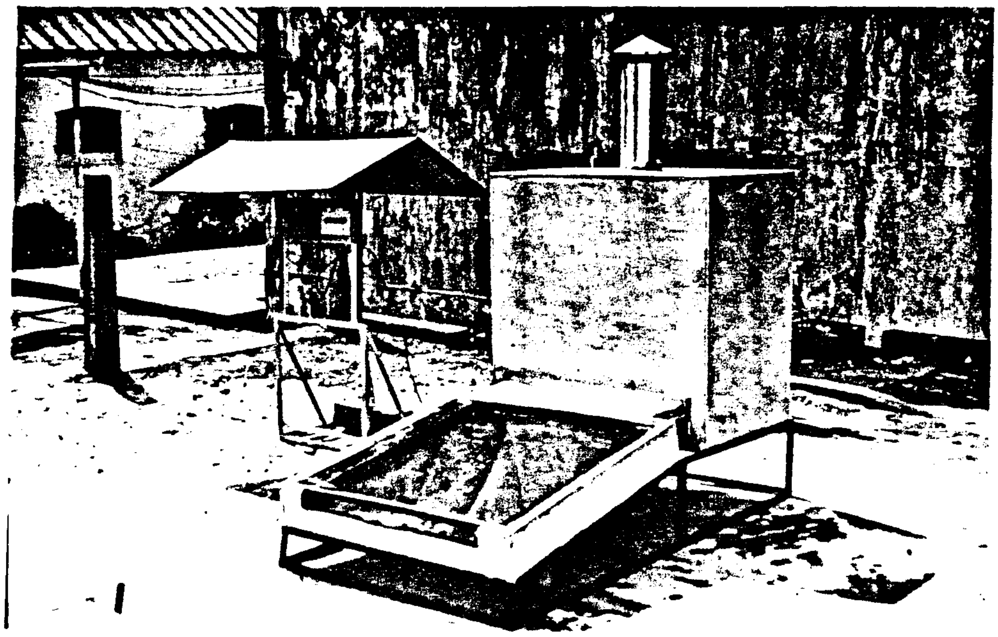

Fig. 1 General front view of dryers

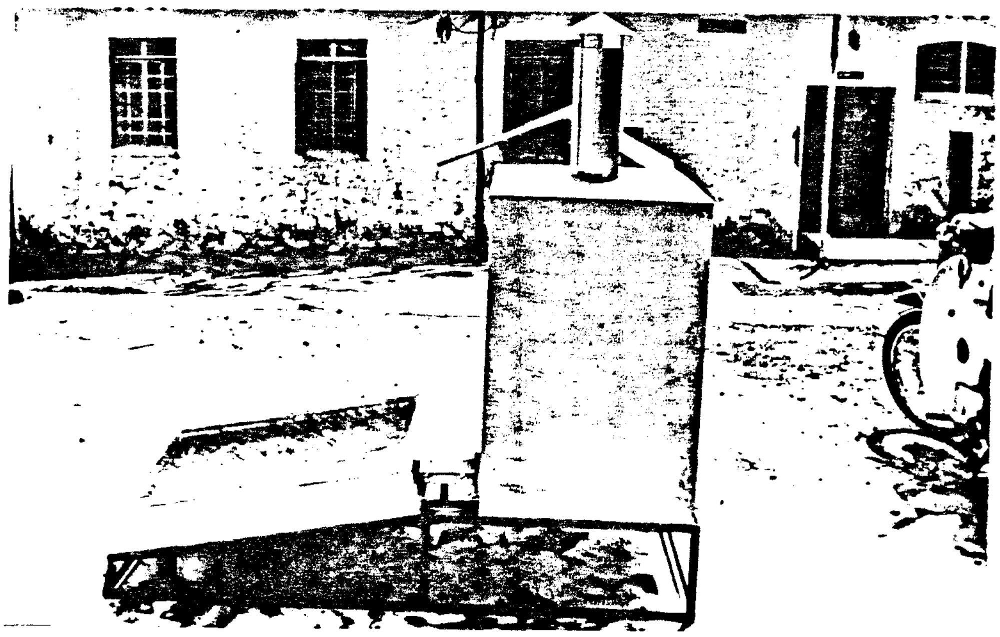

Fig. 2 General side view of dryers

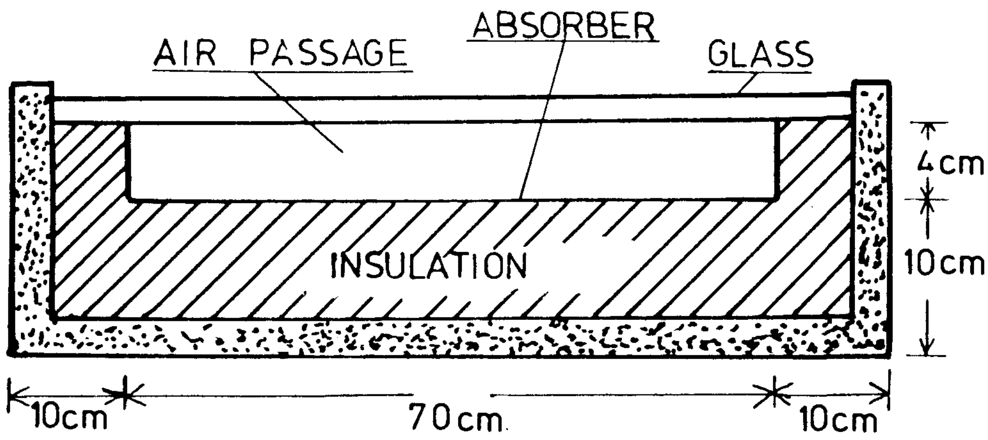

Fig. 3 Cross section of air heater for dryer I showing the single air passage.

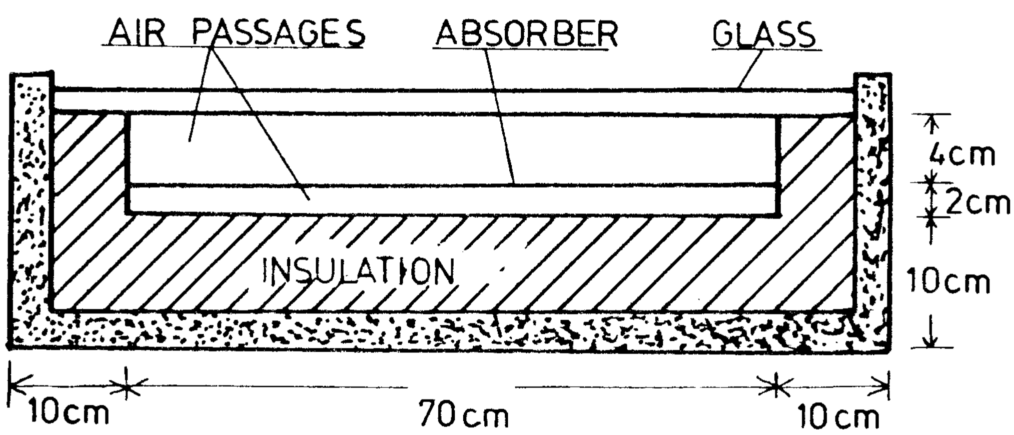

Fig. 4 Cross section of air heater for dryer II showing the double air passage.

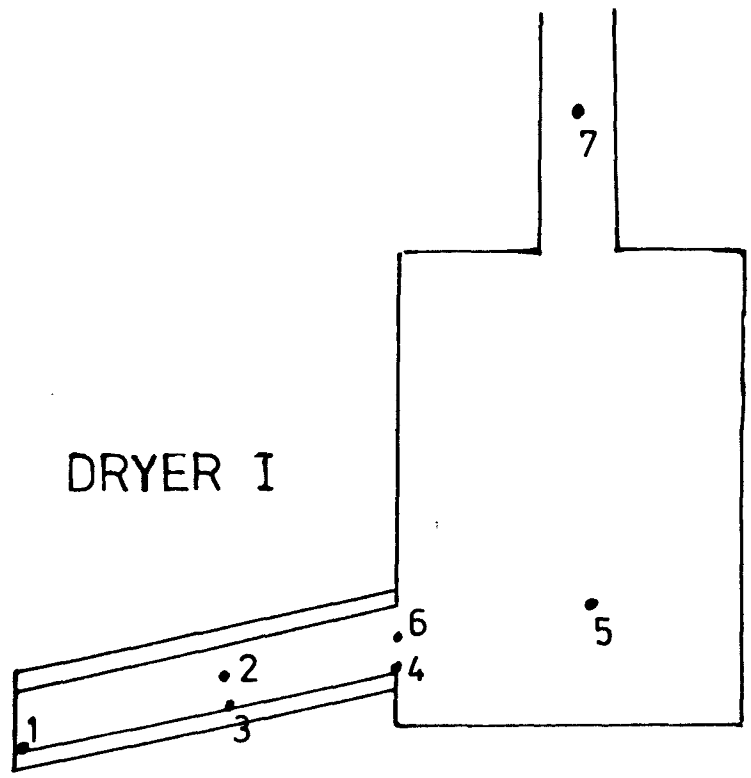

Fig. 5 Diagram showing location of thermocouples in dryer I.

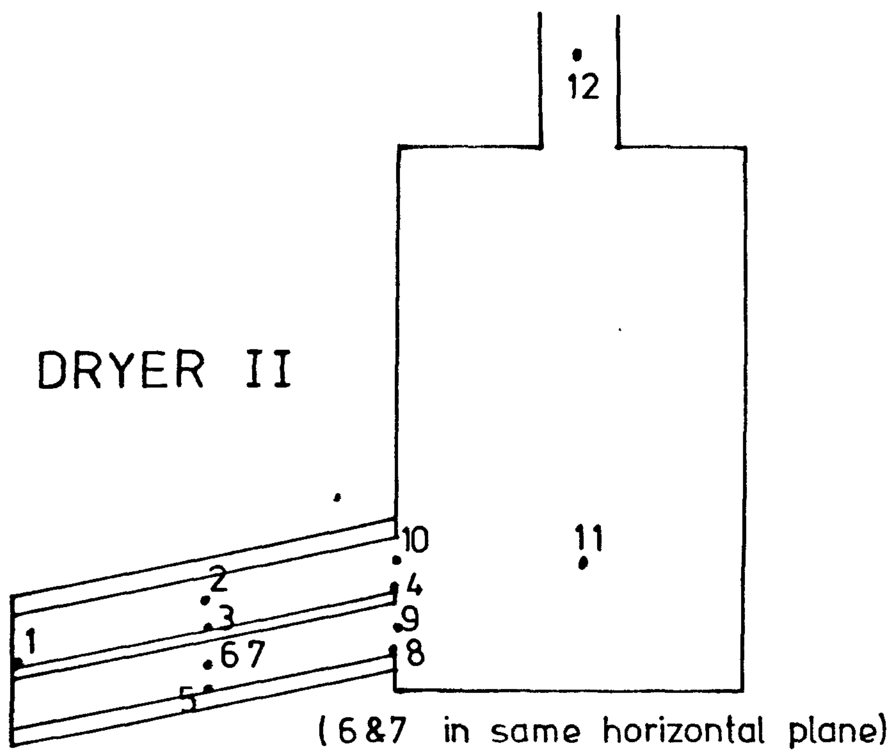

Fig. 6 Diagram showing location of thermocouples in dryer II.

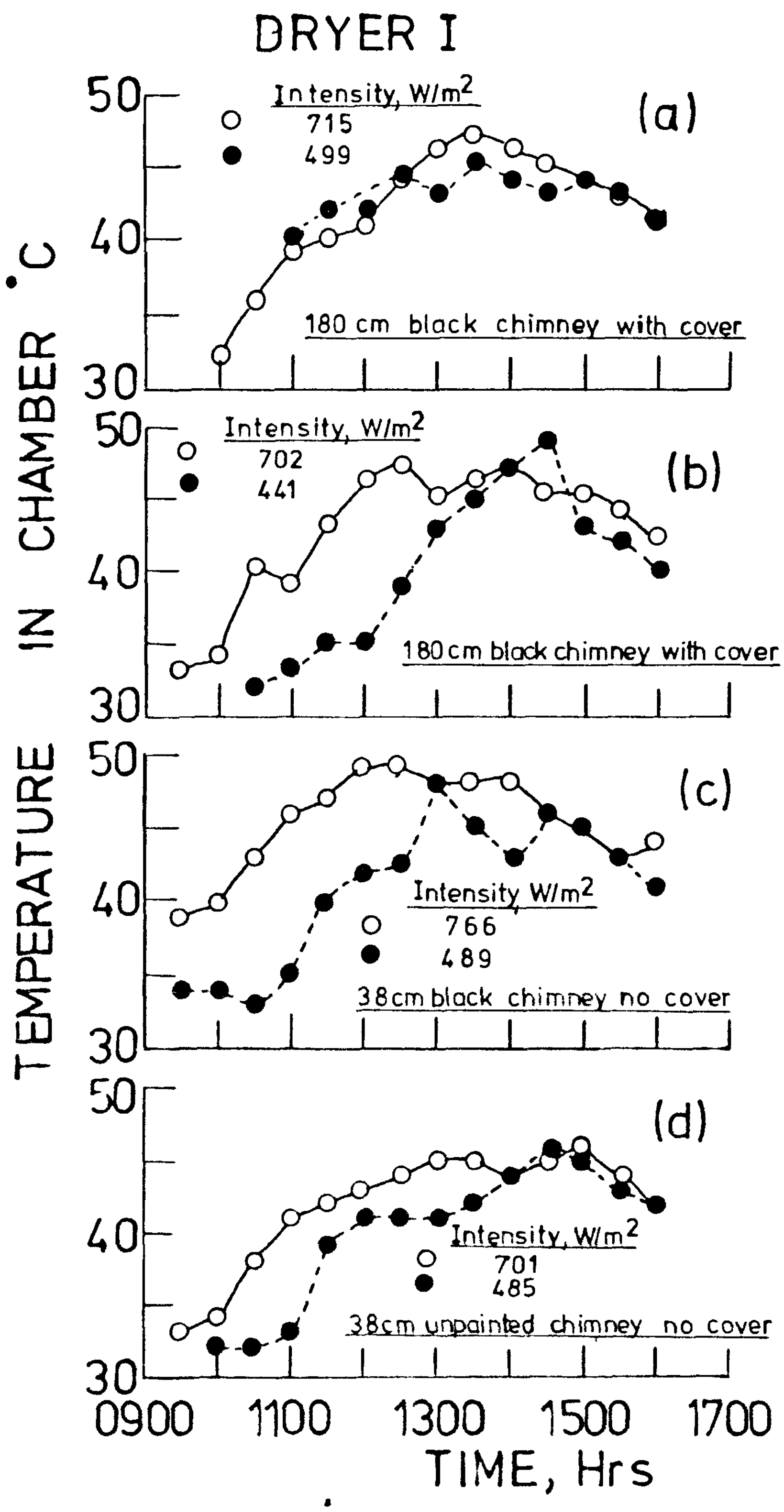

Fig. 7 Effect of mean intensity on chamber temperature for various chimney configurations, for dryer I.

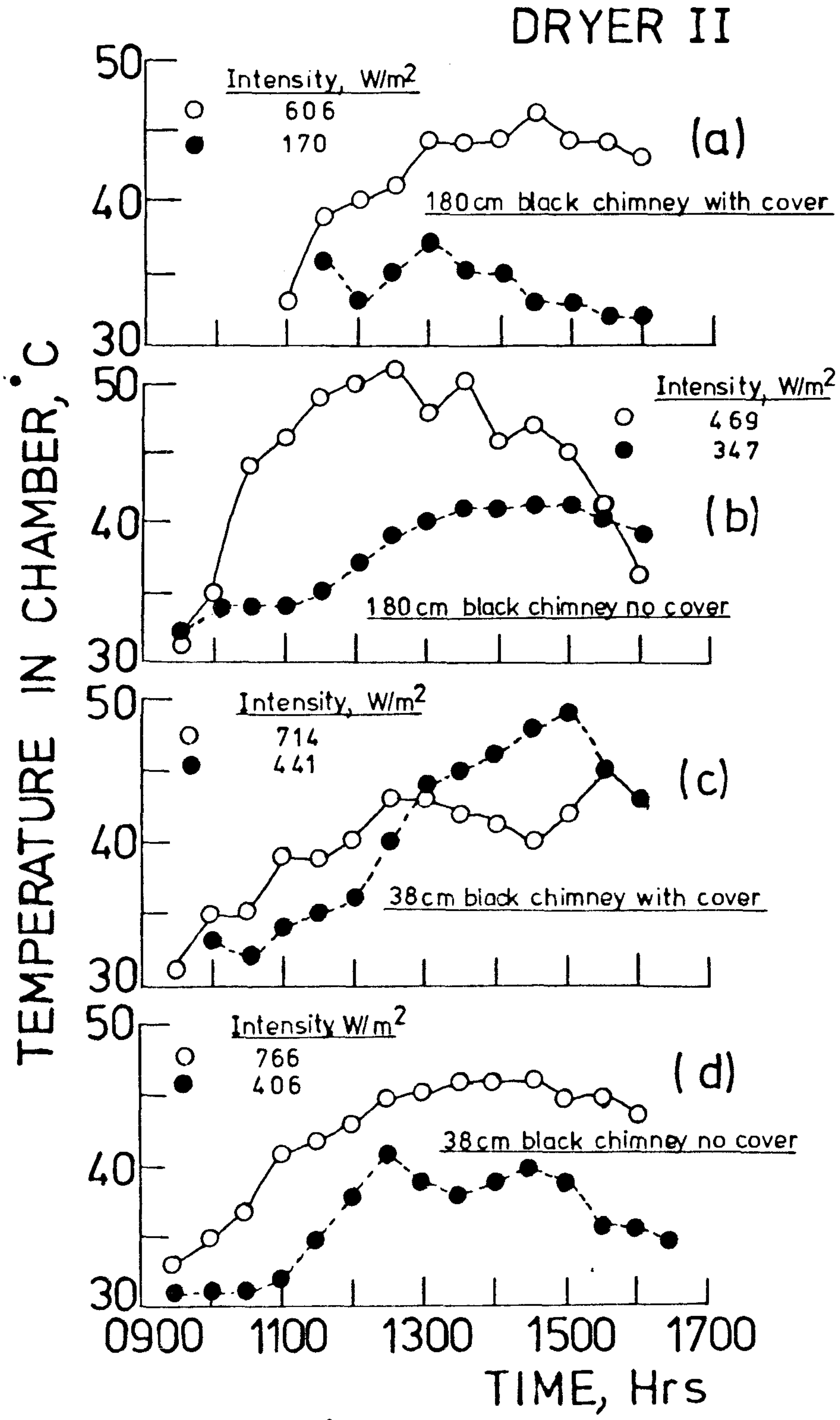

Fig. 8 Effect of mean intensity on chamber temperature for various chimney configurations, for dryer II.

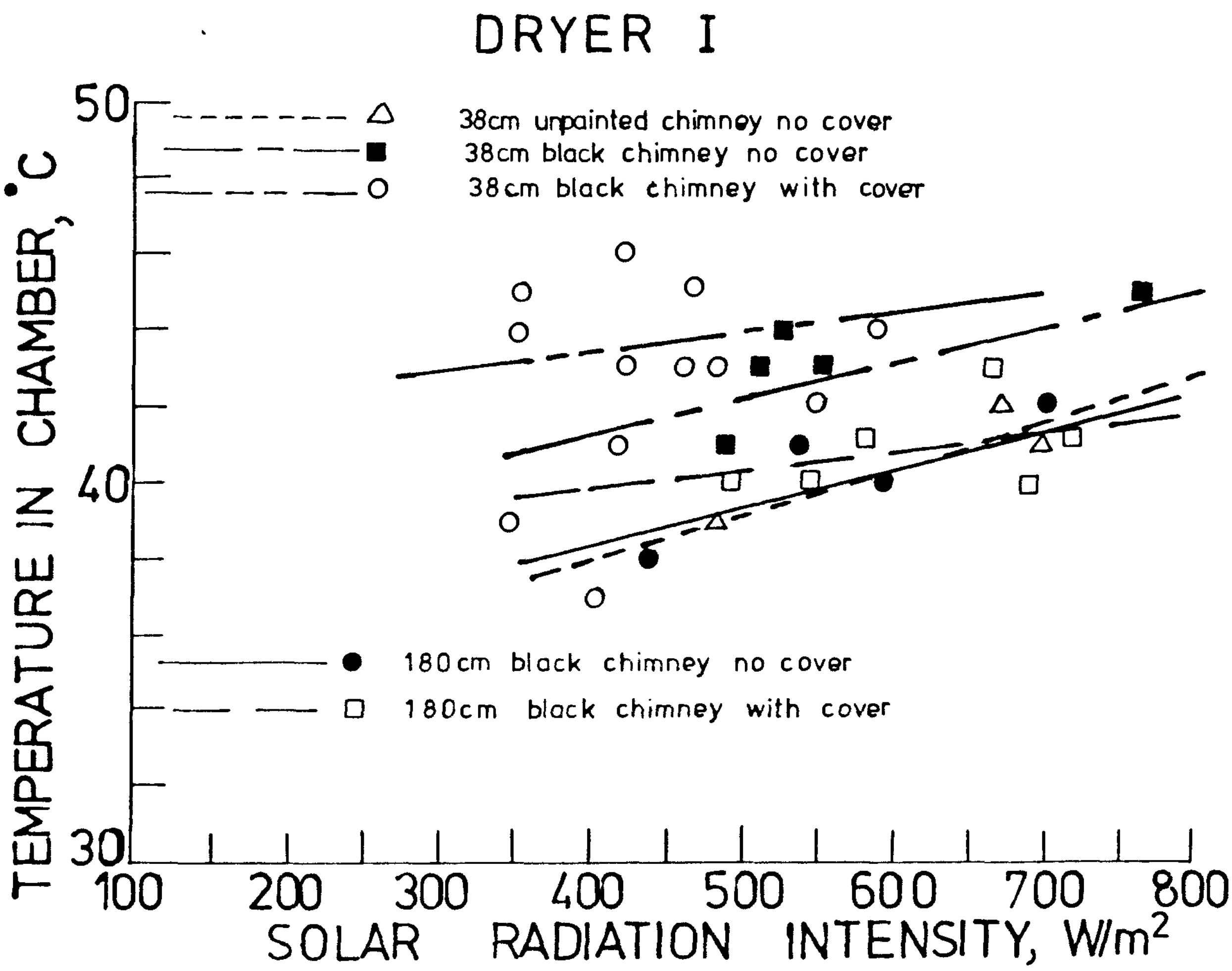

Fig. 9 Variation of daily mean temperature in dryer with mean radiation intensity for various chimney configurations, for dryer I.

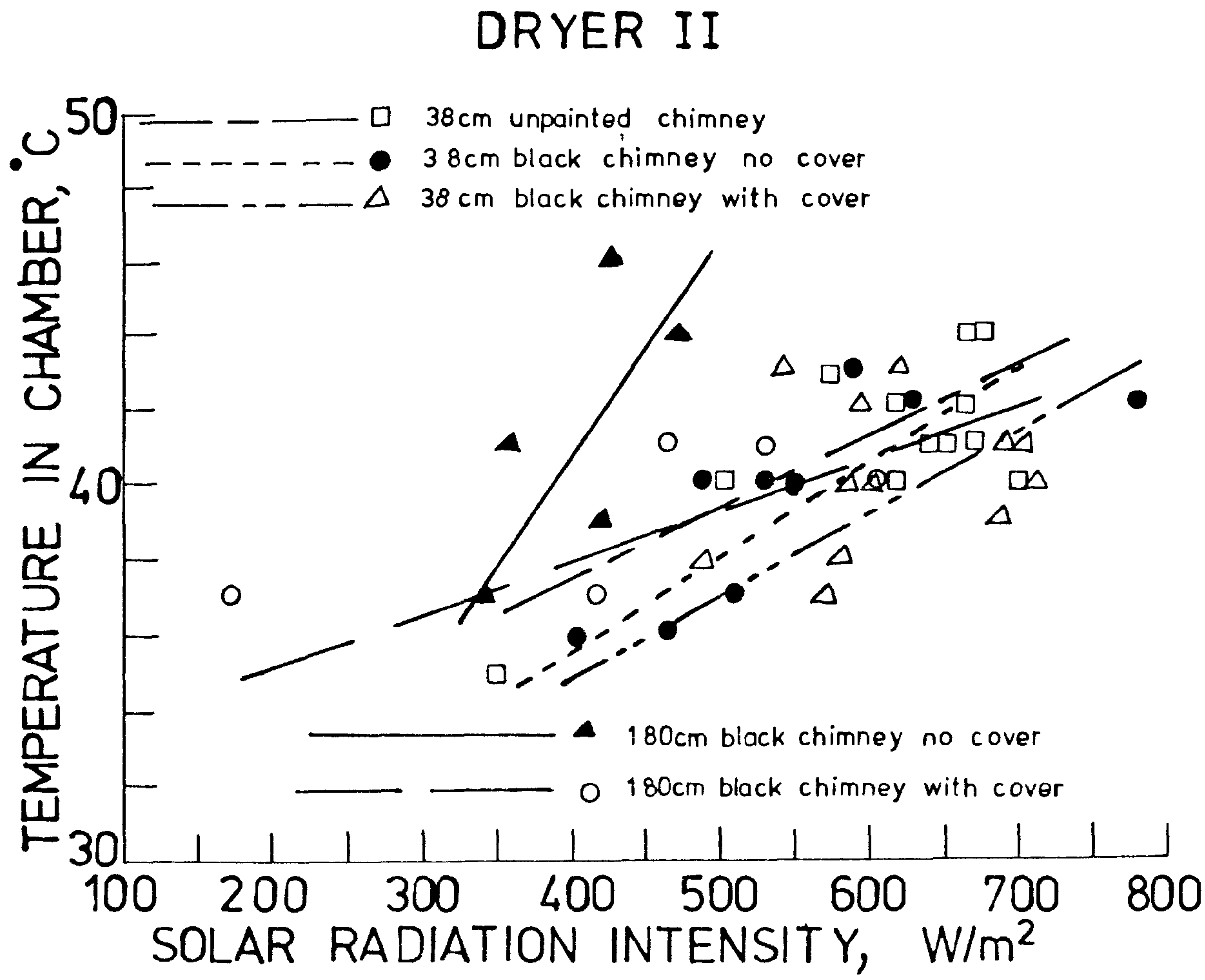

Fig. 10 Variation of daily mean temperature in dryer with mean radiation intensity for various chimney configurations, for prototype II.

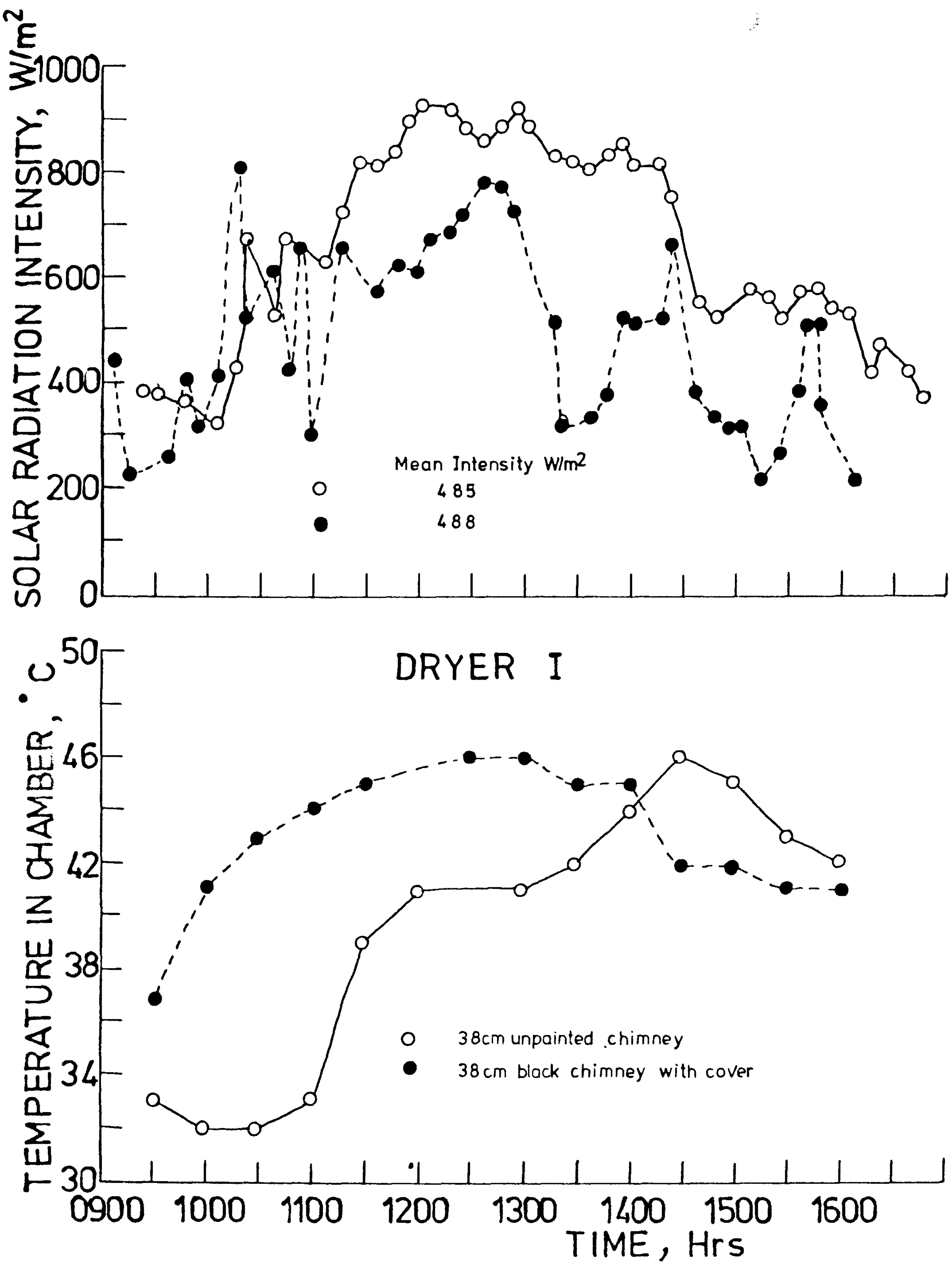

Fig. 11 Comparison of temperatures in drying chamber using two different chimneys for dryer I.

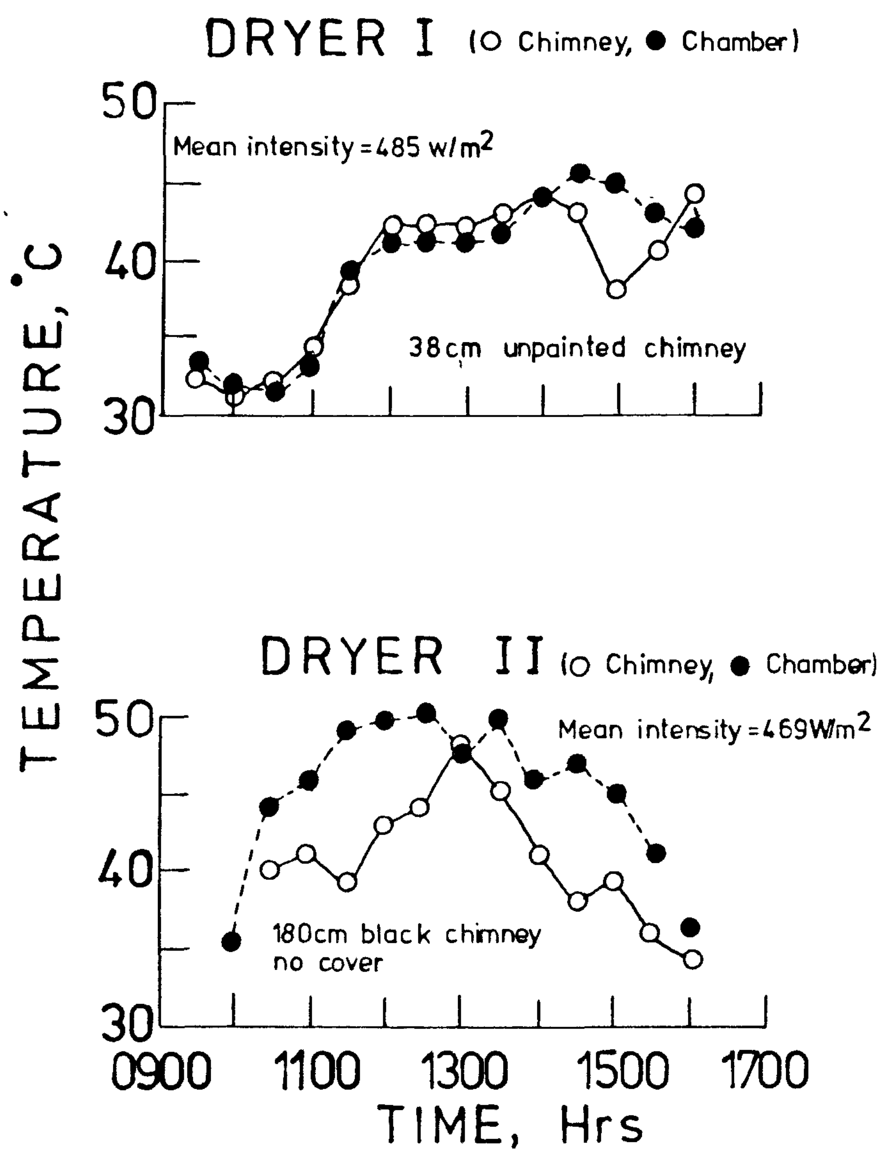

Fig. 12 Comparison of temperatures in chimney and in drying chamber for dryers I and II, under no load conditions.

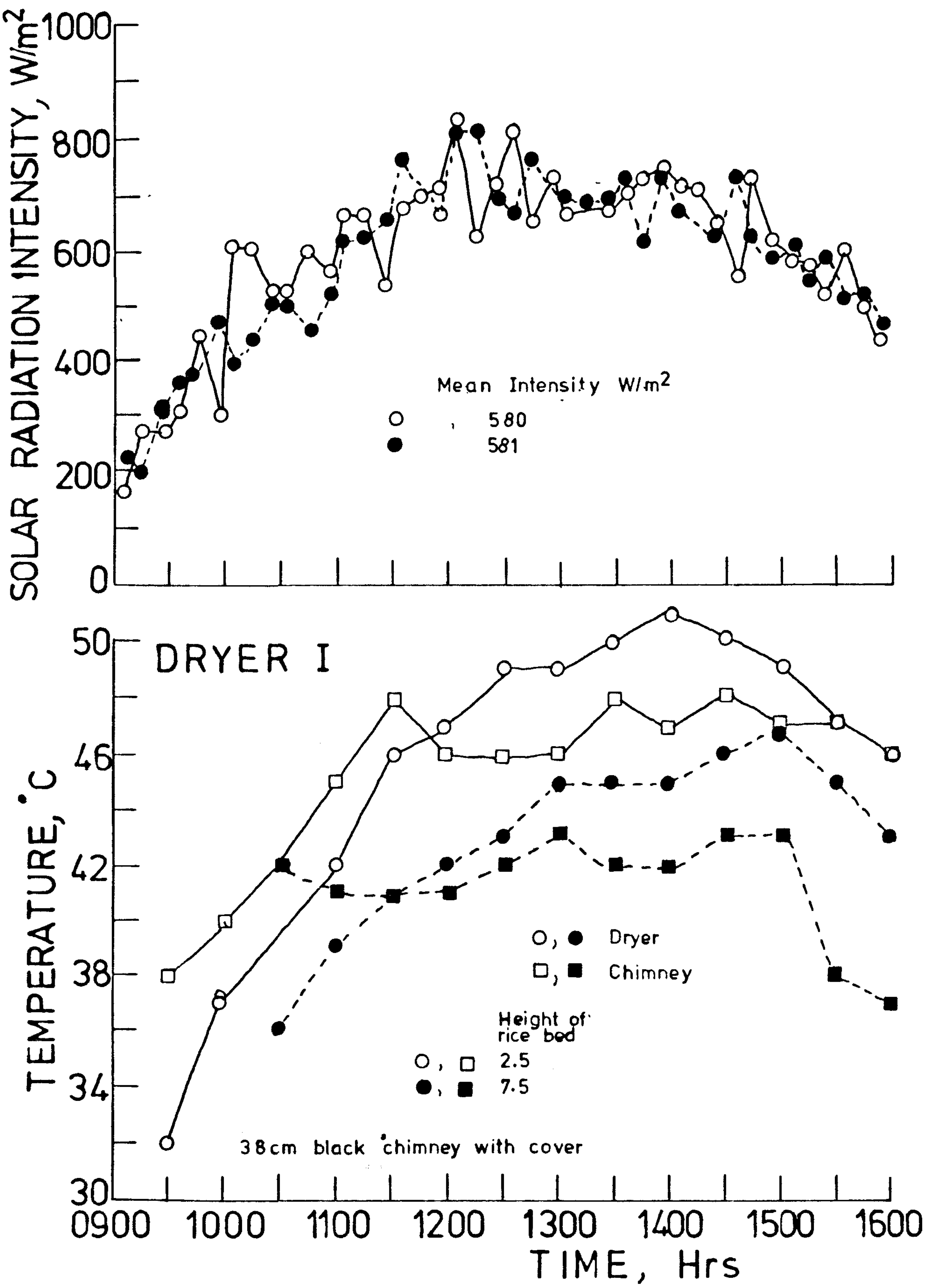

Fig. 13 Temperatures in chimney and drying chamber during tests using rice, for dryer I.

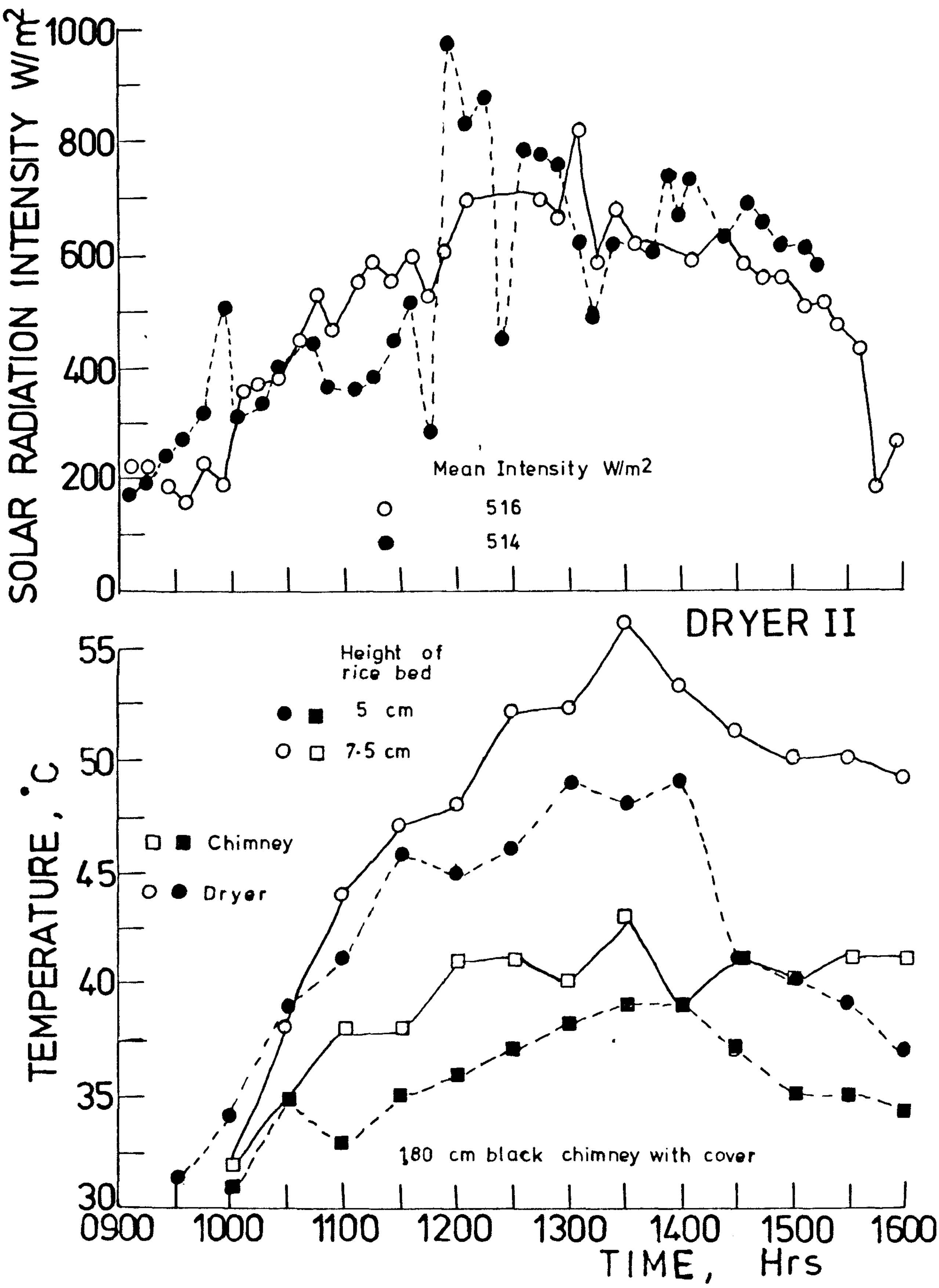

Fig. 14 Temperatures in chimney and drying chamber during tests using rice for dryer II.

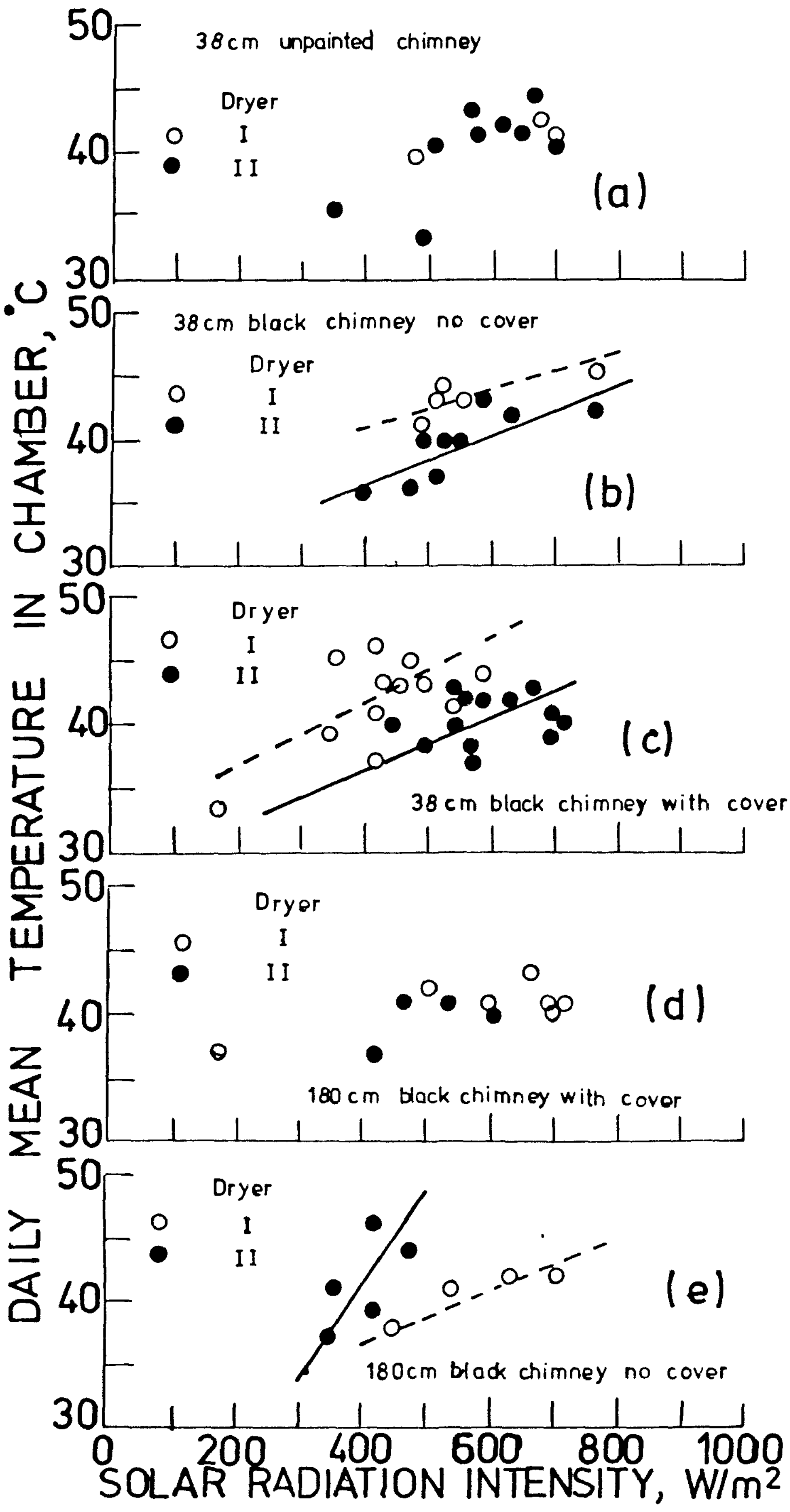

Fig. 15 Effect of air heater design on mean chamber temperatures under no load.

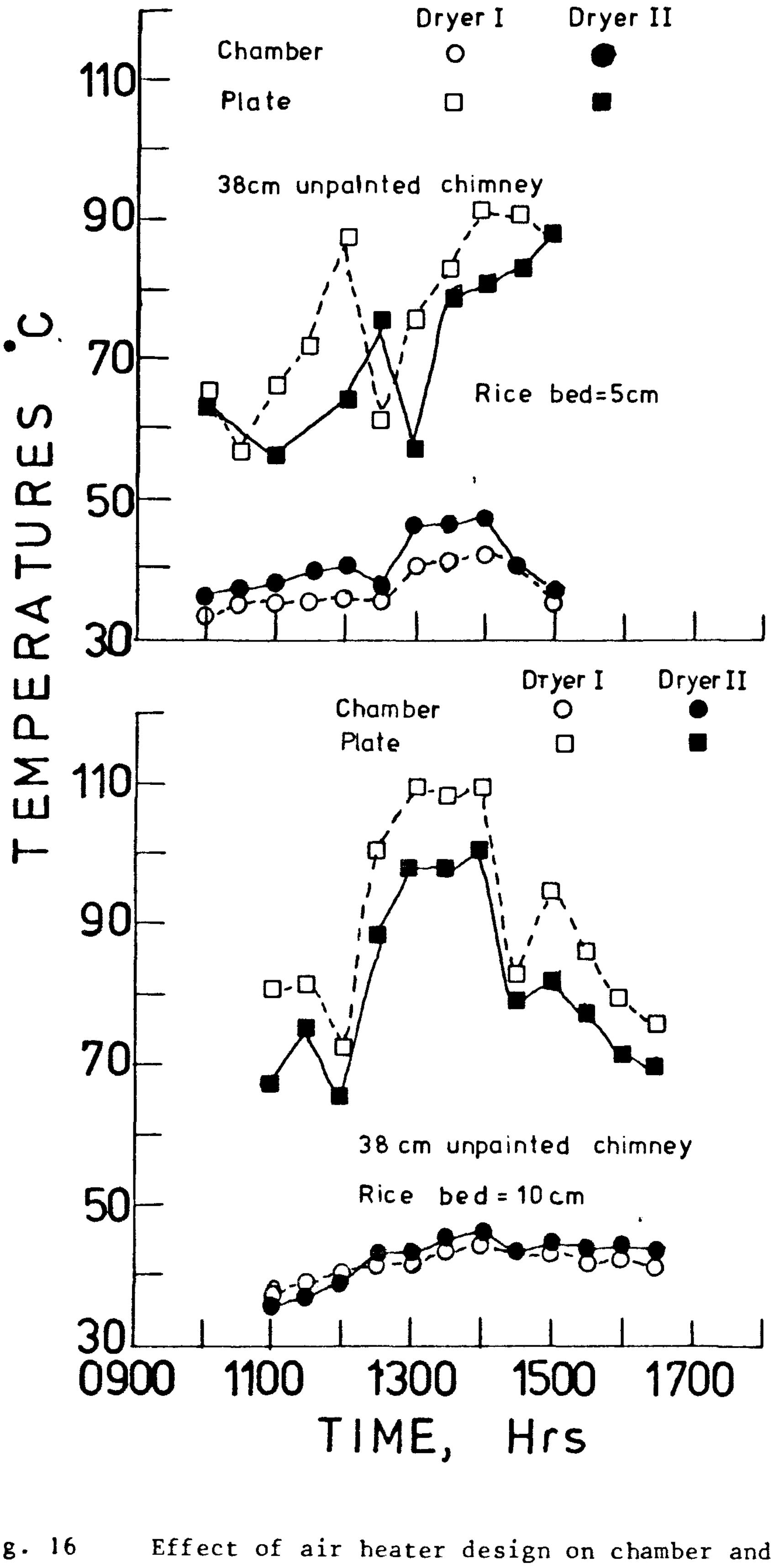

Fig. 16 Effect of air heater design on chamber and absorber plate temperatures, under loaded conditions.