UTILIZATION OF ENGINE-WASTE HEAT FOR GRAIN DRYING IN RURAL AREAS

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ABSTRACT

An attempt was made to measure the availability of waste heat, released from the cooling system of a small engine, which can be utilized for grain drying. An engine powered flat-bed rough rice dryer was constructed and the performance of the dryer with available engine-waste heat was analyzed for 10, 20, 30 and 40 cm rough rice bulk depths with a constant dryer base area of 0.81 m^2. The waste heat was sufficient to increase the drying air temperature 7 to 12°C at an air flow rate of 8.8 to 5.7 m^3/min, while the average ambient temperature and relative humidity were 24°C and 70%. The minimum energy requirement was 3.26 MJ/kg of water removed in drying a 40 cm deep grain bed in 14 h. A forty to fifty centimeter deep grain bed seems to be optimum in order to avoid over-drying in the bottom and under-drying in the top layers. On the basis of minimum energy requirement (3.26 MJ/kg), an estimation was made that the waste heat harvest from an engine of a power range of 1 to 10.5 PS can dry about 0.1 to 1 metric ton of rough rice from 23% to 15% m.c. (w.b.) in 12 h at an average ambient temperature and relative humidity of 25°C and 80%, respectively.

The engine-waste heated grain dryer can be used in the rural areas of non-industrialized countries where electricity is not available.

Key Word : Engine, Waste Heat, Rough Rice, Dryer, Drying, Energy

INTRODUCTION

Rice, one of the world's leading food crops, is usually harvested at moisture levels ranging from 17 to 25% (w.b.) and must be dried to approximately 13 to 15% moisture level (w.b.) to be suitable for storage. The most common and pressing problem in handling wet grain in most non-industrialized countries is delay in sun drying caused by unfavorable weather conditions. Food grains in non-industrialized countries are dried by the traditional method of sun drying. Usually rural farmers spread the grain on beaten earth or woven mats and grain is submitted to adverse effects caused by dust, rain, wind, insect and rodent attack which result in the quality of the dried grains being low. Considerable losses ranging from 10% to 25% can often occur (Excell, 1980). The natural sun drying of a high moisture paddy requires little capital cost, but it has a high labor cost to keep the grain turned regularly and protect it from wet weather. Even then, kernel checking and breaking is a serious set back. Climatic conditions such as the temperature and relative humidity have great influence on sun drying of a paddy. In most tropical countries, climate is characterized by hot and humid air during harvesting. Such air would be of limited use for drying rough rice. The harsh climate condition dictates the need for a more effective method of drying grain. Because of the difficulties in sun drying during wet season, alternative drying method is needed in humid tropical countries.

Research to minimize post harvest losses and for effective utilization of energy resources for crop drying has led to the idea to use waste heat from the internal combustion engine.

An attempt was made for the utilization of engine-waste heat for grain drying with a small dryer bed area and grain depth (Soemangat et al., 1973). They concluded that the energy requirement for grain drying can be minimized with the use of a large bed area, low air temperature and low air velocity.

Abe et al. (1992) reported a preliminary study on the utilization of engine-waste heat for grain drying with a dryer capacity of 140 kg of rough rice. They conducted a single test and less kernel breakage was found than rice dried in the sun or dried too rapidly with high temperature air. They used a separate electric motor to drive the dryer fan which was a serious drawback of their work. This forced them to cover the whole engine with extra housing which is difficult to make and handle and, therefore, impractical.

Basunia et al. (1996) reported a theoretical study on engine-waste heated rough rice dryer performance on the basis of available waste heat. They concluded that engine-waste heat can be utilized as a source of energy for low temperature grain drying.

A review of current literature revealed that very little work has been done on an engine-waste heated dryer. Data are not available on the performance of a dryer, dependent on engine-waste heat, upon which design decisions could be made. Therefore, the present study was conducted with the following objectives :

(i) to measure the availability of engine-waste heat which can be harvested for grain drying; and

(ii) to evaluate the engine-waste heated flat-bed rough rice dryer performance on the basis of available engine-waste heat.

MATERIALS AND METHODS

1. Engine-fan combination and dryer duct system

Figure 1 is a schematic diagram of the drying apparatus used for the experiment. An air cooled four-stroke cycle gasoline engine with displacement of 105 cc, 1.95 PS at 3,000 rpm and 2.5 PS in maximum at 4,200 rpm, 0.25 kg/(PS.h) of fuel consumption and a cooling efficiency of 30% was used. A turbo fan with a maximum air flow rate of 17 m^3/min and static pressure of 260 Pa at a maximum speed of 2,000 rpm was directly coupled with the engine camshaft. The waste heat from the engine heats up the air being forced through the duct to the dryer. The experimental drying chamber was an open-ended plywood box 90×90 cm in cross section and 50 cm deep. A wire screen through which air but not rough rice would pass, was used as the dryer bed. The wire screen was supported by a mild steel rod net to hold the grain mass. A PVC pipe, with 125 mm diameter and 1225 mm long, connects the fan housing with the lower part of the gradually expanding plenum chamber via a 90 degree elbow (**Fig. 1**). The upper part of the plenum chamber, 90 cm square, was attached to the lower part of the dryer. The duct and fan housing were properly insulated so that no heat could be lost by conduction.

2. Measurement of temperature and moisture content

The drying air temperatures at different air flow rates was monitored using copper constantan thermocouples connected to the end of the straight duct, and at three locations at the entrance of the dryer base (**Fig. 1**). Two thermocouples were connected to the engine fin surfaces to determine fin's temperature at different air flow rates. Two thermocouples were also used to record the ambient dry-bulb and wet-bulb temperatures. Thermocouples were connected through an interface of an AD converter (Green kit 77A model) then to personal computer for data collection. The temperature readings from the thermocouples were recorded every 10 min. The thermocouples used for measuring temperatures had an accuracy of ±0.5℃. Air flow rate was measured indirectly by connecting manometers in the straight duct (**Fig. 1**).

After the drying was terminated, the grain was left in the dryer undisturbed for about 10 h. Moisture content was measured immediately after stopping air supply using grain samples collected from the top, middle and bottom layers of the grain bed while drying each depth of grain bed. Grain samples were collected from middle and bottom layers by manual probe and the top layer sample was collected randomly by hand. At each layer, grains were collected from three locations, center, near the wall, and between the wall and the center of the dryer. At each location moisture content was determined individually to determine the moisture gradient across the horizontal direction and then an average was made at each layer. The average moisture content of the entire grain bed was an average of moisture readings from the top, middle and bottom layers. Similarly the average moisture content of the entire grain bed was also measured after 10 h of stopping air supply while drying each depth of grain bed. The moisture content was checked by a single grain moisture meter before drying terminated. The engine was stopped when the average moisture content of the grain bed was found to be approximately 15% (w.b.). Finally, the moisture content was confirmed by the oven drying method, according to the standard procedure of the Japanese Society of Agricultural Machinery.

Medium grain (Japonica type) rough rice was used for the experimental studies. It was grown in the south west of Japan and harvested in October 1995. It was obtained at an average moisture content of 24.7% w.b. and was stored at a low temperature at this moisture level in a refrigerator for the subsequent drying tests. The tests were done in the research laboratories of the Biomechanical Systems Department at the University of Ehime at Matsuyama, Japan.

3. Engine-waste heat

Present gasoline fed internal combustion engines are about 30% effective in output from the energy derived from burnt fuel, another 30% is lost through the exhaust, radiation, friction accounts for 10%, and the remaining 30% is lost through the cooling system. The heat energy required to heat up the drying air is mostly derived from the engine cooling system heat loss. The cooling load P_c of the engine at any given rpm can be determined by the following equation

$$P_c = \eta_c \times \beta \times c_f \times \eta_f \times P_b \qquad (1)$$

where, P_c is the waste heat energy released from the engine cooling system to the air, MJ/h; η_c is the cooling system efficiency, decimal; β is the fuel consumption rate, kg/(PS.h); c_f is the calorific value of fuel, MJ/kg; η_f is the fuel efficiency, decimal and P_b is the break power of the engine at any rpm, PS.

Fuel efficiency is considered 78% and the average calorific value of gasoline is 44 MJ/kg. Thus, from Eqn. (1), the waste heat release to the outside air by the cooling system at any given rpm of the engine is

$$\begin{aligned} P_c &= (0.3 \times 0.25 \times 44.0 \times 0.78) \times P_b \\ &= 2.574 \times P_b \quad \text{MJ/h} \qquad (2) \end{aligned}$$

The total heat energy P_r to be utilized to heat the drying air at any given rpm of the engine is calculated from the following equation

$$P_r = 0.06 \times Q \times c \times \rho \times (t_d - t_a) \quad \text{MJ/h} \qquad (3)$$

where, P_r is the amount of heat energy received by the drying air, MJ/h; 0.06 is the units conversion factor; Q is the volume flow rate of drying air, m^3/min; c is the specific heat capacity of drying air, kJ/(kg°C); ρ is the density of drying air, kg/m^3; t_d and t_a are the temperature,°C of drying air and ambient air.

Generally an air volume of 1 m^3/(PS.min) is considered appropriate for an air-cooled engine for the purpose of designing. However, when the fan is directly coupled to the engine camshaft, the air volume is increased during operation of the engine.

RESULTS AND DISCUSSION

1. Performance of engine-fan combination

The performance of the engine-fan combination was studied before the actual test with rough rice bulk in the dryer. The static pressure versus airflow curve and the system curves by considering 10, 20, 30 and 40 cm depths of grain bed in the dryer are plotted on the same graph **(Fig. 2)** in order to know the possible air flow rates for the depths considered. Each system curve includes the losses in the straight duct, 90 degree elbow, gradual expansion of the plenum chamber and depth of rough rice bed considered. All these losses were calculated according to the procedure described by Brooker et al. (1992). A curve plotted as pressure drop versus air flow is called a system curve. The static pressure and the air flow at the point of intersection are those at which the system will operate. From the stability point of view, it seems to be more appropriate to operate the engine at 3,000 rpm at which the fan rpm was 1,500. It was also observed that the energy transmitting efficiency of the drying air from the engine-waste was highest at 3,000 rpm of the engine for the measured drying air flow rates.

Possible air flow rates were 5.6, 6.6, 7.7 and 9.4 m^3/min for the assumed 40, 30, 20 and 10 cm depths of rough rice bed in the dryer, respectively, at 3,000 rpm of the engine

(**Fig. 2**). It was observed that drying air temperature varies with the ambient temperature at the same air flow rate and at the same engine speed. A negligible difference was observed between the temperatures measured at the end of the straight duct and at the entrance of the dryer. Therefore, the average of the temperatures, measured at the end of the straight duct for a particular air flow rate, was considered as the drying air temperature for that air flow rate and used in the calculation of energy.

The estimated energy released as waste heat from the engine cooling system, measured heat energy received by the drying air, energy losses from the system and waste energy receiving efficiency of the drying air at different measured air flow rates at 3,000 rpm of the engine are presented in **Table 1**. The average ambient temperature and relative humidity were 25℃ and 77%, respectively. Waste heat energy released from the engine cooling system and heat energy received by the drying air were calculated from Eqns. (2) and (3), respectively. Heat energy losses due to various causes were estimated to be the difference between the estimated heat energy released by the engine cooling system at a given rpm and the heat energy received by the drying air. The average energy losses are for comparison purposes only and do not imply that the loss rate will remain constant over the period of the drying experiment. Since no instrument was available to directly measure the system energy losses, one can only speculate about the source of these losses. Although the fan housing, duct system and plenum chamber were properly covered with insulating material, it is probably safe to assume that a portion of the heat was absorbed by the air in the heating fan housing, duct and plenum chamber. Engine-waste heat was sufficient to increase the drying air temperature some 6 to 27℃ depending on the measured air flow rate. It can be observed from **Table 1** that about 93% of the waste heat released from the engine cooling system was transmitted to the drying air at 3,000 rpm of the engine. Efficiency seems to be very high, because part of the exhaust energy was also received by the drying air while the fan was in operation. This was not directly due to harvesting of exhaust gases, rather exhaust waste heat energy was received by drying air from the surface of the exhaust passage. So it was not harmful for the grain, rather it was extra benefit to the system. The fan also helps proper cooling of the engine. It was observed that at the same ambient temperature, and engine speed, engine fin temperature was 30℃ higher, than the engine running with a fan coupled at the camshaft. This will help to increase the operating life of the engine.

2. Dryer performance

Variations of ambient, drying air and engine fins temperatures with the drying period in drying 10, 30 and 40 cm depths of grain bulk are shown in **Fig. 3**. A similar trend in temperature variations were also observed in drying a 20 cm depth of grain bed. It can be observed from **Fig. 3** that as the depth of grain bulk was increased the temperature difference between the drying and ambient air was also increased. The temperature difference was almost constant throughout the drying period while drying a particular depth of grain bed. As the engine speed was kept constant at 3,000 rpm, the air flow rate and the temperature and relative humidity of the drying air also varied depending upon the depth of rough rice bulk and ambient conditions.

The main experimental results are summarized in **Tables 2** and **3**. Experimental average air flow rates were 5.7, 6.9, 7.7 and 8.8 m^3 /min while drying 10, 20, 30 and 40 cm depths of grain bed, respectively. The difference between the theoretical **(Fig. 2)** and measured air flow rates was small. It was observed that within the range of 5.7 to 8.8 m^3/min of air flow, engine-waste heat was sufficient to increase the drying air temperature 12 to 7°C, while the average temperature and relative humidity of ambient air were 24°C and 70%. The moisture content of all rice was approximately 24.7% (w.b.) at the beginning of drying and was dried to an overall average of approximately 15.5% m.c.(w.b.). Average bulk density of rough rice was approximately 605 kg/m^3, according to the volume occupied by the grains in the dryer. The initial weight of moist grain of 10, 20, 30 and 40 cm depths of grain bed in the dryer are shown in **Table 3**.

Results show the drying time required to bring the average approximate moisture content 15.5% (w.b.) from the initial 24.7% m.c. (w.b.) were 9, 9, 12 and 14 h in drying 10, 20, 30 and 40 cm depths of grain bed, respectively **(Table 3)**. Time required in drying 10 and 20 cm depths of grain bed was same because of, comparatively, high ambient air relative humidity while drying a 10 cm depth of grain bed. Another reason was that, as the depth of grain bed was reduced, drying air quickly moved through the grain bed without proper utilization due to its higher velocity. The moisture gradient was found negligible in the horizontal direction at the end of drying. The moisture gradients between the top layer and bottom layer were found to be 0.4, 1.6, 2.2 and 3.4 % (w.b.) of 10, 20, 30 and 40 cm depths of grain bed, respectively, at the end of drying. These results show that the moisture gradient between the top layer and bottom layer is a problem in a deeper grain bed. The moisture gradient increased as the depth of grain bed was increased. The moisture gradient was considerably high in 40 cm depth of grain bed. Undisturbed, continuous air flow, fixed bed drying has an inherent problem of over drying where the drying air is introduced, particularly with higher air temperatures which tend to lower the moisture content below the desired 13% w.b. (Angladette, 1963). But in an engine-waste heated dryer, drying air temperatures are not so high. It was 29.2 to 36.4°C depending upon the depth of grain bed in the dryer at an average ambient temperature 24°C. The average moisture content of the entire grain bed determined immediately after stopping the engine was 1.5 to 2% more than the moisture content determined after 10 h, while drying each depth of grain bed. This indicates that it is better to under-dry the grain by 1.5 to 2% m.c (w.b) than the safe moisture level for storage and leave the grain in the dryer undisturbed for few hours to avoid over drying.

With the measured energy transmitted to the drying air, the energy required to remove one kg of moisture from the grain to bring the final average moisture content at approximately 15.5% (w.b.) were calculated for 10, 20, 30 and 40 cm depths of grain bed **(Table 3)**. Results show that as the depth of grain bed increased, the energy required to remove one kg of moisture from the moist grain was decreased. The maximum energy requirement was 6.64 MJ/kg of water removed from the moist grain while the depth of the grain bed was 10 cm **(Table 3)**. The minimum energy requirement was 3.26 MJ/kg of water removed in drying a 40 cm depth of grain bed which was lower than the average energy requirement of 3.6 MJ/kg (Sharp, 1982) of a highly efficient mechanical dryer. In principle, a low temperature dryer, by using the moisture absorbing capacity slightly over the ambient air, may require less energy than the latent heat of water vaporization (~2.5 MJ/kg) to remove moisture from the grains. This indicates that there is little chance to increase the dryer base area with this particular engine-waste heat while keeping the drying period fixed at 14 h. On the basis of minimum energy requirement (3.26 MJ/kg) and available engine-waste for drying, an estimation was made to find the amount of grain that can be dried by engine-waste heat. The waste heat from the engine of power range 1 to 10.5 PS, with dryer base area of 0.4 to 4.5 m^2 and air flow rate of 3 to 31.5 m^3/min, can dry about 0.1 to 1 metric ton of rough rice from 23% to 15% m.c. (w.b.) in 12 h at an average ambient temperature and relative humidity of 25°C and 80%.

CONCLUSIONS

Engine-waste heated dryer performance was analyzed. Results have shown promise for this type of grain drying unit, especially in the major rice growing regions where the engine used for pumping irrigation water and rice milling purposes can also be used for grain drying.

The 30 to 37°C drying air temperature can be attained under most tropical conditions with waste engine heat, thus no additional capital investment nor operating cost is necessary for the supplemental heating of drying air. Even the provision can be easily made to use the same engine simultaneously for dual purposes, like drying and milling or irrigation, as the power required for fan operation is very low as compared to the engine power. The main advantages of the engine-waste heated dryer is that it can be easily built by local technicians using locally available materials, and less kernel breakage and stress checks will occur than when rice is improperly dried in the sun or too rapidly dried with highly heated air. The use of this flat-bed dryer, in rural areas where electricity is not available, should then encourage the harvesting of improved rice varieties with field moisture contents as high as 25 % (w.b.) to minimize harvest shatter losses.

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Table 1 Estimated waste energy released from the engine cooling system and measured heat energy received by the drying air at an engine speed of 3,000 rpm

Air flow rate (m^3/min.)	Drying air temperature rise (°C)	Energy released from cooling system (MJ/h)	Energy received by drying air (MJ/h)	Energy loss (MJ/h)	Energy receiving efficiency of the drying air (%)
0.91	26.9	5.02	1.66	3.36	33.07
1.57	24.5	5.02	2.61	2.41	51.99
2.73	16.3	5.02	3.02	2.00	60.16
3.40	16.0	5.02	3.69	1.33	73.51
4.63	13.1	5.02	4.12	0.90	82.07
5.82	11.8	5.02	4.64	0.38	92.43
6.55	10.5	5.02	4.65	0.37	92.63
7.61	9.0	5.02	4.64	0.38	92.43
9.67	6.8	5.02	4.46	0.56	88.84

Ambient temperature 25°C, relative humidity 77%

Table 2 Air flow characteristics for different depths of grain bed at an engine speed of 3,000 rpm

Depth of grain bed (cm)	Air flow rate (m^3/min.)	Static pressure (Pa)	Drying air temperature (°C)	Drying air r.h.* (%)	Ambient air temperature (°C)	Ambient air r.h.* (%)
10	8.8	50	29.2	44.3	22.3	81.8
20	7.7	98	32.3	31.6	24.1	67.2
30	6.9	120	33.8	25.0	24.3	68.2
40	5.7	138	36.4	24.6	24.7	64.1

*r.h. = relative humidity

Table 3 Effect of depth of grain bed on the energy requirement and moisture gradient to dry to 15.5 % m.c.(w.b.) using an engine speed of 3,000 rpm (average initial m.c. 24.7 %.)

Depth of grain bed (cm)	Initial weight of grain (kg)	Bottom layer m.c % w.b.	Top layer m.c % w.b.	Moisture gradient % w.b.	Total drying period (h)	Energy required (MJ/kg)
10	48.5	15.5	15.9	0.4	9	6.64
20	96.0	14.8	16.4	1.6	9	3.70
30	141.8	14.3	16.5	2.2	12	3.33
40	193.2	13.5	16.9	3.4	14	3.26

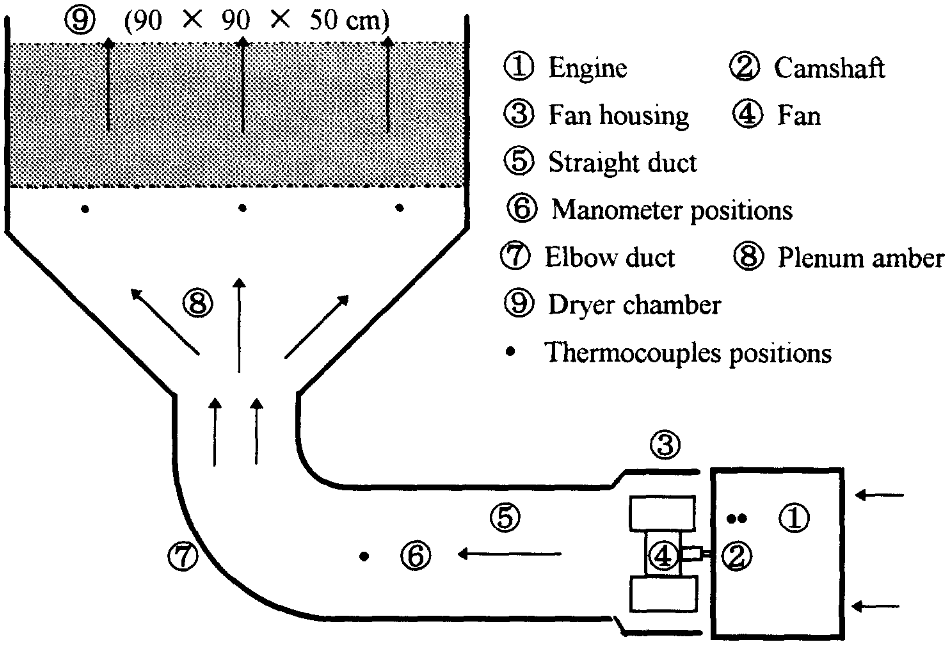


Fig. 1 Schematic diagram of the drying apparatus used for the experiment

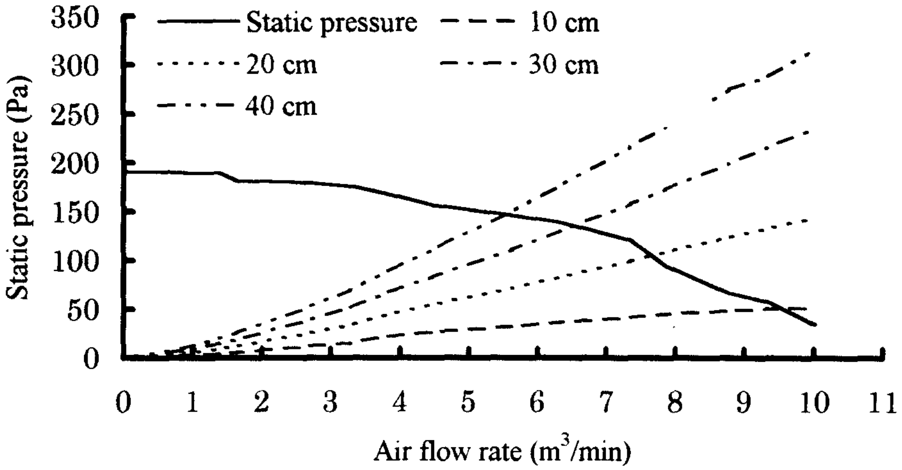
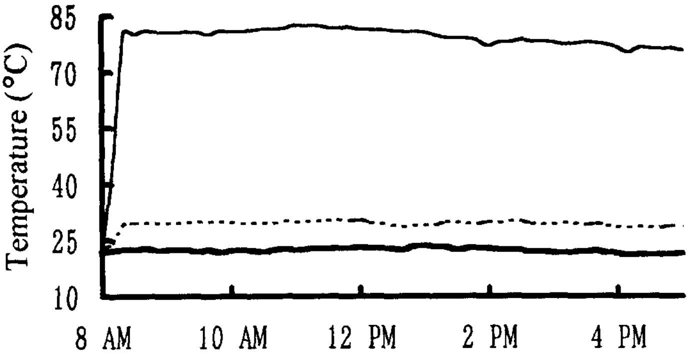
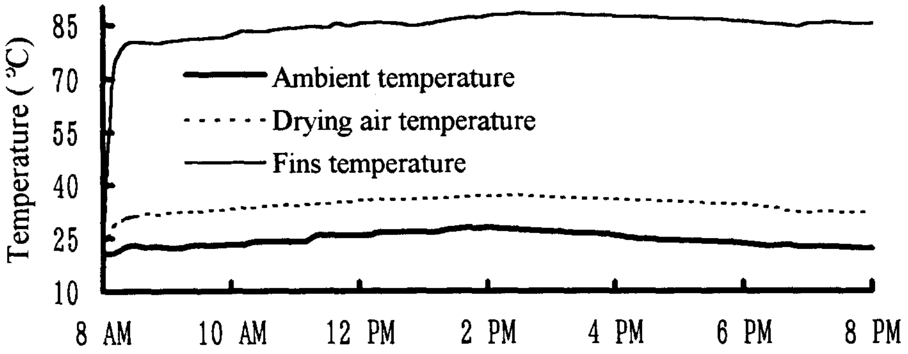


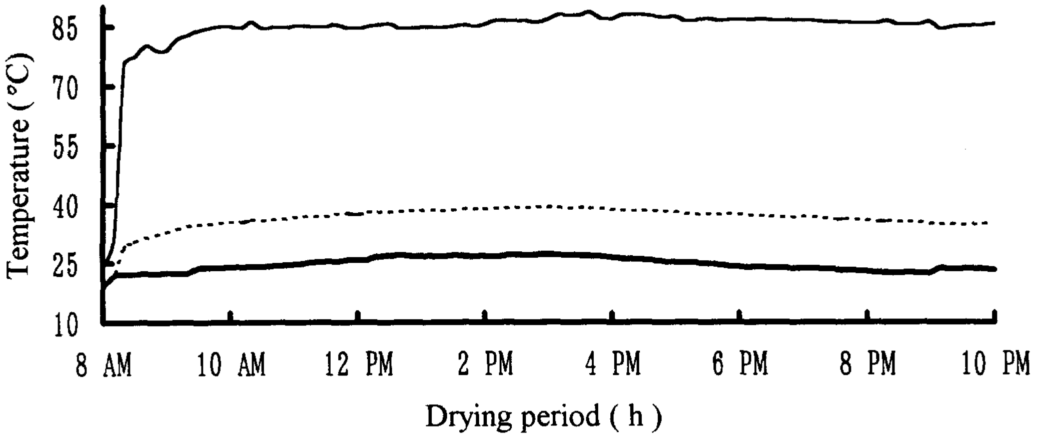
Fig. 2 Measured static pressure versus airflow curve and the system curves of the fan for 10, 20, 30 and 40 cm rough rice bulk depths considered in the dryer, at an engine speed of 3,000 rpm



(a) 10 cm -deep grain bed



(b) 30 cm -deep grain bed



(c) 40 cm -deep grain bed

Fig. 3 Variations of ambient, drying air and engine fin temperatures with drying periods for 10, 30 and 40 cm grain bed depths.