

An improved passive solar dryer and a neuro-fuzzy system to control it

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INTRODUCTION

Drying agricultural produces farmers can add aggregate value to their products and obtain better prices.

Nowadays, there is a great knowledge about drying, and also a wide variety of dryers i.e. electric, fuel-burning, solar ones, etc.

Passive solar dryers are a good alternative for drying agricultural products, specially in places where there is no availability of electric energy or in situations where the use of fossil fuels is unaffordable.

The main design of passive solar dryers uses air as a working fluid to transmit heat to the drying stuff and remove the evaporated water from it.

One problem of this design, and also of the majority of dryers, is the low efficiency of the system, which normally ranges between 10 and 30%. Also, the lack of control of key variables as temperature or drying rate, normally lead to decreases in the quality of the dried product.

The goal of this research was to develop an improved passive solar dryer, which can obtain a good quality final dried rice, while optimizing the use of solar energy, reducing costs and keeping the design simple.

On doing this, two methods were researched: improvement of the design and use of a Neuro-fuzzy control system.

II LITERATURE REVIEW

2.1 Drying.

Drying is the removal of a liquid (water vapor) from a solid through thermal means. This definition emphasizes the basic fact that the evaporation of a liquid (or a decrease in the moisture content at any point in a body) is invariably linked with a corresponding flow of heat.

Transfer of heat inward from the surroundings is accompanied by the transfer of mass in the form of water vapor outward from the wet body to its surroundings [1].

2.1.1. Heat transfer.

Heat transfer can be done through: convection, conduction or radiation.

a. Conduction.

Transfer of energy in heat conduction takes place by the exchange of momentum of random thermal motion of the molecules with neighboring molecules.

Transfer of heat by conduction is defined by:

$$q = -k.A.dt/dl \quad (1)$$

This equation takes the following generalized form for unsteady one-dimensional flow of heat in a body whose thermal conductivity, density and specific heat may vary both with temperature and with position within the body:

$$d^2t/dl^2 = d(k/\rho c. (dt/dl))/dl \quad (2)$$

Thermal conduction is low in gases and vapors and very high in many metals, as copper.

b. Convection.

In a liquid or gas, heat conduction will often be small in comparison with heat transfer by the bodily movement of some portions of the fluid with respect to the containing walls or other portions of the fluid, or with transfer by means of radiant energy [1].

For many purposes, convectonal heat transfer is correlated by:

$$q = h.A(t - t_g) \quad (3)$$

c. Radiation.

Transfer of energy by thermal radiation between two bodies, takes place proportionally to the difference of the fourth powers of their absolute temperatures.

$$q = C. A. (T_1^4 - T_2^4) \quad (4)$$

In the majority of dryers, the energy for evaporation is conveyed to the drying food particles by a stream of heated air (mainly convection). The air stream also carries away the water vapor from the surfaces of the particles .

However, air has relatively low heat transfer capacity and the heat transmission coefficient between a solar plate and air is low, [2] and [3].

2.1.2. Drying stages.

On a drying process we can distinguish two stages:

- The constant rate period, where drying takes place mainly in the hull [4], and the drying rate depends strongly on the air flow rate [5]; and
- The falling rate period, where the internal redistribution of moisture is the most important factor, and it is accelerated by the rise of material temperature. Neither wet-bulb depression nor air velocity has any further appreciable effect on the drying time, but the material temperature does, [1] and [5].

In wheat, the majority of the drying does not occur in the constant rate period, but only in the falling rate period, and it is controlled by the internal rate of diffusion [6].

2.1.3. Efficiency on dryers.

A wide range of efficiencies can be found on dryers. In order to be able to make comparisons, it is better to compare the energy requirements of dryers. A range of 1,4 to 11 MJ/kgH₂O evaporated, and an average value of 5.6 MJ/kgH₂O is found in the literature [7],[8] ,[9] and [10]. Scarce information is available on energy requirements on solar dryers, but an average value of 7 MJ/kgH₂O can be estimated.

2.1.4. Factors affecting efficiency

- The input moisture content of the grain, the wetter the grain the higher the efficiency because it is easier to remove water vapor from wet grains [11]. Oshita et al, reports that the specific heat of rice was found to vary linearly with the moisture content [12].
- The temperature inside the dryer, the closer the temperature inside the dryer to the ambient temperature, the greater the efficiency, [13] and [1].
- The air flow rate, high airflow rates near the ambient temperature have greater efficiency. However, air velocities greater than 6 m/s produce crack generation of the paddy rice [14]. Also, as the temperature rises, it is advised to diminish the air flow [15].
- The dryer design; e.g. bin configuration [16], flow path length, V-corrugated or flat absorber plates [17].

There are some factors whose influence is not clear because of contradictory results, such as type of bed (fluidized, semifluidized or stationary bed) [9] versus [13].

Of all these factors, the most important seems to be the airflow. As Yamashita [18] reports, normally around 1/3 of the energy supplied to dryers is lost with the exhaust air.

2.1.5. Factors affecting quality.

a. Rice temperature.

High temperature during drying may cause grain fissures in rice, and also the rice taste quality may be lowered. Temperatures of 45 °C or less are recommended for the drying, [19].

On sun drying on open surface, the ratio of cracked rice increased by the average temperature of grain surface, and more than 20% of cracked rice was observed even when the grain surface radiation temperature was kept under 34 °C, [20].

b. Drying rate.

To reduce grain fissuring, the drying rate should be less than 1% - 1.5%w.b./h, [21] and [22]. This seems to be related with the speed of giving off water that the grains can resist without damaging their internal structure.

c. Air relative humidity.

The crack rate of rice increases with decrement of air relative humidity, [19]. Low moisture rice will fissure when it is subjected to an environment from which it can rapidly absorb moisture. This moisture adsorbing environments can be produced naturally by temperature and relative humidity changes in the ambient air.

d. Tempering.

Pausing during drying decreased the unevenness of moisture content of individual rough rice kernels and reduced the cracking drying, [23]. However normally dismissed, tempering is a highly advisable technique to improve rice quality and reduce energy requirements on dryers. As grains do not dry evenly (due to differences on structure, initial moisture content, size, etc.), to let them rest whereby an homogeneous moisture content can be achieved, is a good practice.

Tempering in a ratio of 1:3 to 1:5 (drying time : resting time) is recommended.

There are also other factors which increase efficiency and/or quality, but have serious drawbacks from the economic or simplicity of use viewpoint, as: transmission of heat by radiation [8]; increasing the specific area of the absorber plate [17]; separation of kernels prior to drying according to the difference in physical and/or hygroscopic characteristics [24]; MacFarlane and Bruce [25], point that timeliness costs were too-site specific to be included in a general cost function model..

As can be seen from the literature review, air is the main working fluid used on dryers. It is heated mainly for two reasons:

- a. To pass it through (or over) the grain and carry away the water vapor from the surfaces of the grains (humidity carrier), and
- b. To transmit energy to the grains (heat carrier).

The second reason seems misplaced, since air has a low heat capacity and the heat transmission coefficient between the absorber plate of the drier and air is low.

Therefore, we hypothesize that the use of copper plates to transmit heat to the grain by conduction, instead of using air convection, should allow us to reduce the energy requirements of passive solar dryers. Nevertheless, air will not be discarded, it will be used but its main objective will be to act as a humidity carrier.

2.1.6. Drying through conduction.

On using a heating plate to dry granular materials through conduction, the heat transfer coefficient depends mainly on [26]:

- the thermal properties of the granular material,
- the particle size, and
- the depth of the bed.

Of this 3 factors, the only one that can be changed through design is the third one, so we have to center our improved design around the bed depth.

2.1.7. Costs.

The cost of a dryer is influenced for many factors:

- annual usage, the higher the annual usage, the lower the cost.
- temperature inside the plenum, with the optimum in 50 to 60 °C, [27].
- Solar radiation, the higher the radiation the lower the cost.

Nakagawa [28], reports a drying cost of 0.02 US\$/kg in a solar circulating type grain dryer. Drying wheat from 20 to 15% wet basis could cost between 1.2 to 2.2 US\$/ton, [25].

2.2. The Intelligent Control System

Neural Networks (NN) and Fuzzy Systems (FS) are used to estimate input-output functions for complex systems (2 or more input variables, nonlinear relations).

Both are trainable dynamical systems, using numerical rather than symbolic representation.

They encode sampled information in a parallel-distributed framework.

Unlike statistical estimators, they estimate a function without a mathematical model of how outputs depend on inputs. Consequently, they are model-free estimators, [29].

2.2.1. Neural Networks.

Neural Networks (NN) are systems that are deliberately constructed to make use of some organizational principles resembling those of the human brain, [30].

NNs consist of a number of interconnected processing elements or neurons. The connections between neurons hold a value, called weight, which allow a weighted input

to the neuron.

2.2.1.1. Integration and activation functions.

A neuron receives information (inputs) through its weighted connections. These inputs are integrated into one value or net input through an integration function. This integration function can be linear, quadratic, polynomial, etc.

Next, this integrated value is compared with a threshold value. The result of this comparison is fed to an activation or transfer function. This activation function determines the output value of the neuron. The activation function can be linear or sigmoid.[31]

2.2.1.2. Connections.

Neurons can be combined to make a layer of neurons.

According to the connections between layers, we can classify NN as:

- Feedforward, when no neuron output is an input to a neuron in the same layer or in a preceding layer.
- Feedback, when neurons outputs can be directed back as inputs to same or preceding layer nodes. Feedback NN that have closed loops are called recurrent NN. Feedback NN in which neurons output is directed back as input to neurons in the same layer is called lateral feedback.

2.2.1.3. Learning rules.

Learning rules are the algorithms through which the NNs change themselves to better estimate the relation between input and output data.

Broadly speaking, there are 2 kinds of learning rules.

2.2.1.3.1. Parameter learning rules.

They update the connecting weights. These learning rules are the most utilized. They can be subdivided as:

- Supervised learning, when the NN is supplied with desired input-output pairs of data.
- Reinforcement learning, when the NN is supplied with few detailed information (e.g. result is wrong) that in the previous one.
- Unsupervised learning, when none information is supplied to the NN about what the outputs should be or whether they are correct, [30].

2.2.1.3.2. Structure learning rules.

They focus on the change in the network structure, including the number of neurons and their connection types.

2.2.2. Fuzzy Systems

Fuzzy set theory may be considered an extension of classical set theory. While classical set theory is about “crisp” sets with sharp boundaries, fuzzy set theory is concerned with “fuzzy” sets whose boundaries are “grey”, [29].

A Fuzzy System (FS) is the means by which linguistic rules that qualitatively express a control strategy may be interpreted on a computer.

It is composed of fuzzy sets. Each fuzzy set is characterized by a membership function that associates with each discrete value of the given variable a membership value in the interval between 0 and 1. A particular membership quantitatively represents the degree to which the corresponding value of the variable is a member of the fuzzy set.

The elements of a FS are: the fuzzifier, the rule-base, the inference engine and the defuzzifier.

2.2.2.1. The fuzzifier.

It transforms crisp input data (e.g. moisture content = 28%) into suitable linguistic values (e.g. rice moisture is high). This transformation is done through a Fuzzy membership function.

There are many kinds of membership functions: triangle, trapezoidal, bell shaped, sigmoidal, etc. But the shape is generally less important than the number of curves and placement. From 3 to 7 curves are recommended to cover the required range of an input value.

2.2.2.2. The rule base.

It stores the knowledge or expertise about a process, through linguistic rules of the form “if A is then B is” Where A and B are fuzzy variables and T and S are particular values (fuzzy sets) that those variables can assume. The propositions before the “then” word are called antecedents, and those after the “then” are called consequents.

The antecedents in a rule are combined using three kind of fuzzy operators.

- AND, it uses the minimum weight of all the antecedents.

- OR, it uses the maximum value of all the antecedents
- NOT, it subtracts a membership function from 1 to give the complementary function.

2.2.2.3. The inference engine.

It is the heart of any FS. There are 3 main types:

- Fuzzy reasoning of the first type, in this mode of reasoning, the fuzzy control rule leads to the control decision.
- Fuzzy reasoning of the second type or Tsukamoto's method, with linguistic terms as monotonic membership functions. This is a simplified method based on fuzzy reasoning of the first type in which the consequent is required to be monotonic.
- Fuzzy reasoning of the third type, where the consequent of a rule is a function of input linguistic variables.

2.2.2.4. The defuzzifier.

It allows to calculate the output crisp value. Two methods are widely used:

- The center of area method, which takes the center of gravity of the fired consequents memberships sets.
- The height method, which takes the value of the biggest contributor.

2.2.3. Neuro-Fuzzy Systems.

Both, NN and FS have some drawbacks. For example NN do not allow the use of rule of thumbs or linguistic knowledge, while FS can not learn by themselves. Furthermore these disadvantages are complementary with the strengths of the other method.

Therefore a hybrid of these two methods, called a Neuro-fuzzy system (NFS), can have sinegertic results.

On a NFS, the NN provides the connectionist structure (fault tolerance and distributed representation properties) and learning abilities to the fuzzy system, and the fuzzy system provides a structural framework with high level fuzzy IF-THEN rule thinking and reasoning to the NN, [30].

III MATERIALS AND METHODS

3.1. The solar dryer.

The main objective of our improved design is to use conduction heat transfer rather than convective heat transfer between the dryer and the rice.

Therefore, from equation 1, we can see that we have:

- To use a material with high thermal conductivity. Due to its high conductivity and low price, copper was chosen as the material of the plenum chamber. Although contact with copper can produce an off-flavor in dairy and other products, as pointed by Hall [30], this is not a problem on rice drying.
- To increase the contact area between rice and metal. Here, a problem of efficiency versus costs arose, therefore we decided to use a perforated holding plate, on which the rice is laid on, connected through vertical plates to the absorber plate.
- To use high temperatures on the dryer. This factor is constrained by the recommended maximum temperature of rice of 45 °C on drying.
- To shorten the distance of heat flow. On doing this two directions must be considered, vertical heat flow direction (depth of bed rice) and horizontal heat flow direction (horizontal distance between vertical plates.)

As the material and maximum temperature are known, it follows that the only remaining factors that we have to determine are:

- The bed depth of rice, and
- The horizontal distance between vertical copper plates.

3.1.1. Preliminary Research

During the design, accurate data about the best disposition of bed depth and distance between vertical plates could not be found.

In order to obtain data, firstly it was thought to build a mathematical model. But, after some research it was realized that it would be very difficult to implement, and the accuracy achieved would be low.

Consequently, we decided to build some experimental models and do preliminary tests to research the influence of bed depth and distance between vertical plates over the performance of the dryer.

Three bed depths: 10, 20 and 30 mm, and three distances between vertical plates: 10, 25 and 50 mm; were decided. Accordingly, 9 experimental models of the solar dryer were built.

Five tests were performed during the month of July. The place was the roof of the Agricultural Engineering Workshop. The data obtained from these preliminary tests was used for the design of the improved solar dryer.

The main results of this preliminary research were:

- An average energy requirement of 4,5 MJ/kgH₂O evaporated was obtained.
- The shallow bed depth of 10 mm was statistically less efficient than the 20 or 30 mm ones, due to the higher temperatures reached by the grain and plates in the former.
- The distance between plates of 50 mm was statistically less efficient than 10 or 25 mm. This was thought to be due to the fact that as distance between plates increases the percentage of total heat transmitted to the grain through convection (less efficient) increases.
- To improve the dryer, bed depths can be increased, but not distances between plates. It was recommended to use bed depths of 30 mm or more, and distances between vertical plates of 25 mm.
- The drying rates achieved were too high, with an average of 2.4%/h
- The rice temperatures were sometimes higher than the maximum allowed value, with an average of 42 °C.
- A drying cost of 0.03 US\$/kg of dried rice was achieved, but this cost depended heavily on the annual usage.

3.1.2. The improved solar dryer.

Taking into consideration the preliminary results pointed above, and also easiness of construction, low cost, high efficiency and good final quality of the rice, the improved solar dryer was designed.

The improved solar dryer (see fig.1 and fig. 2) consists of:

- a. A glass cover, on the top, to produce the greenhouse effect. It is made of standard glass 3 mm thick.
- b. An absorber copper plate, 30 mm under the glass cover. It is black painted on the surface facing the glass. The copper plate is 2 mm thick.
- c. A holding copper plate, which holds the grain. It has 4 mm diameter holes, spaced at 10 mm of distance in a grid pattern all over its area.
- d. Vertical copper plates, connecting the absorber and holding plate. They are 70 mm height and 200 mm long. They are soldered to the absorber and holding plates to ensure a good heat transmission, as recommended by Hollands and Shewen [19], forming a honeycomb like structure.

- e. Wood frame, that acts as the skeleton to assemble the elements above. It is made of planks 20 mm thick.
- f. A gate, on the inlet of air, to control the quantity of air entering the dryer. This gate was controlled by a stepper motor, controlled at its turn by the Neuro-fuzzy control system. The width of the gate is the same as the width of the dryer (200 mm) and has a height of 15 mm.

The equipment used for the tests of the solar dryer was (see fig. 3 and fig. 4):

- a. 1 thermocouple type "T", used to measure the temperature of the central layer of grain.
- b. 1 scale, used to weigh the rice. The moisture content of the rice was determined by the difference of 2 weight readings (over and elapsed time), divided by the initial weight of rice. This scale has a precision of 0.1 gr.
- c. 1 piranometer, to measure the solar radiation.
- d. 1 digital humidity meter, to measure the air humidity. This instrument also gave readings about ambient temperature.
- e. 1 stepper motor and its controller
- f. 1 analog/digital converter type AZI-120, 98-FBI
- g. 1 computer NEC 85 to run the Neuro-fuzzy system.

During the tests, the next procedure was followed:

- a. The moisture content of the rice to be used in the test was determined through the oven method.
- b. Rice was loaded into the dryer until the desired bed depth was obtained.
- c. The rice and dryer were weighed (together), and by difference with the weight of the empty dryer, the initial rice weight was determined.
- d. The dryer was set, on the roof of the Agricultural Engineering Workshop. The dryer was laid flat (i.e. none or zero tilt angle).
- e. Values of the initial rice moisture content and the final desired rice moisture (that is the target rice moisture content) were fed into the computer.
- f. The system began to work automatically, and it would finish when the target rice moisture content was obtained.
- g. As a control, for comparison, a sample of rice (with the same moisture content) was laid on a table, with a bed of the same depth as the solar dryers'. This rice has not any glass or cover, so this treatment can be assumed to be a direct sun drying method.

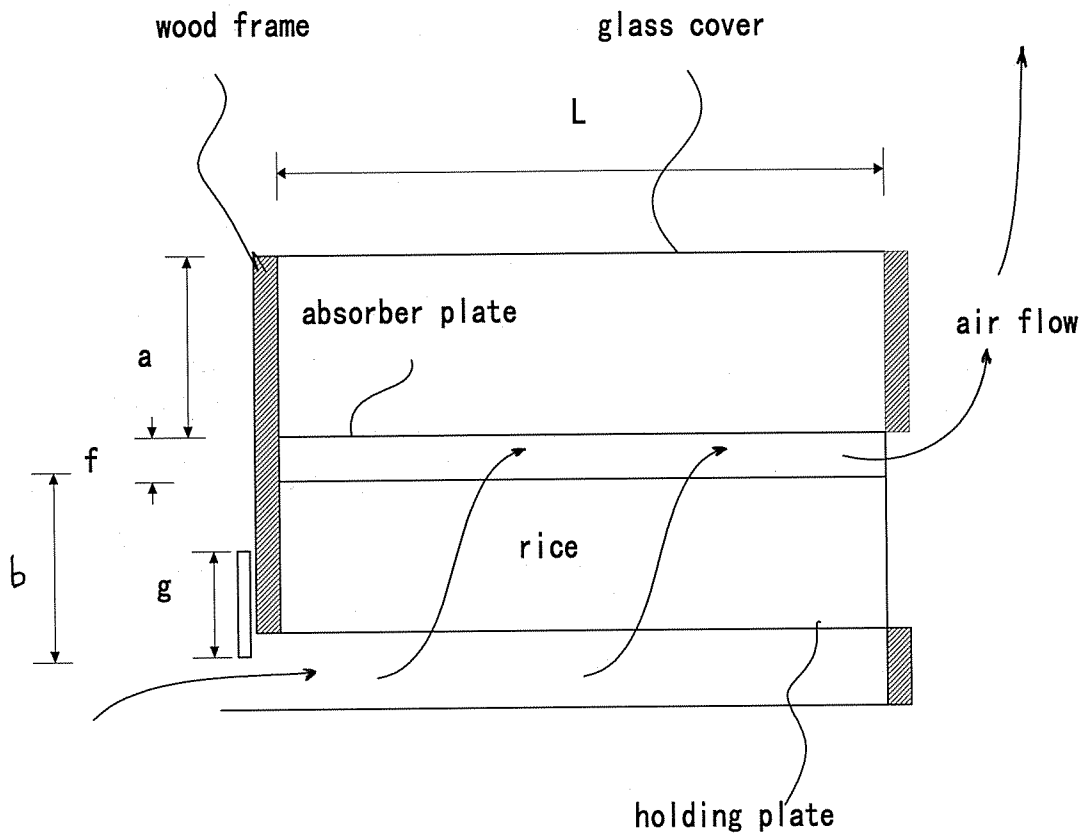


Fig. 1 Schematic view of the solar dryer

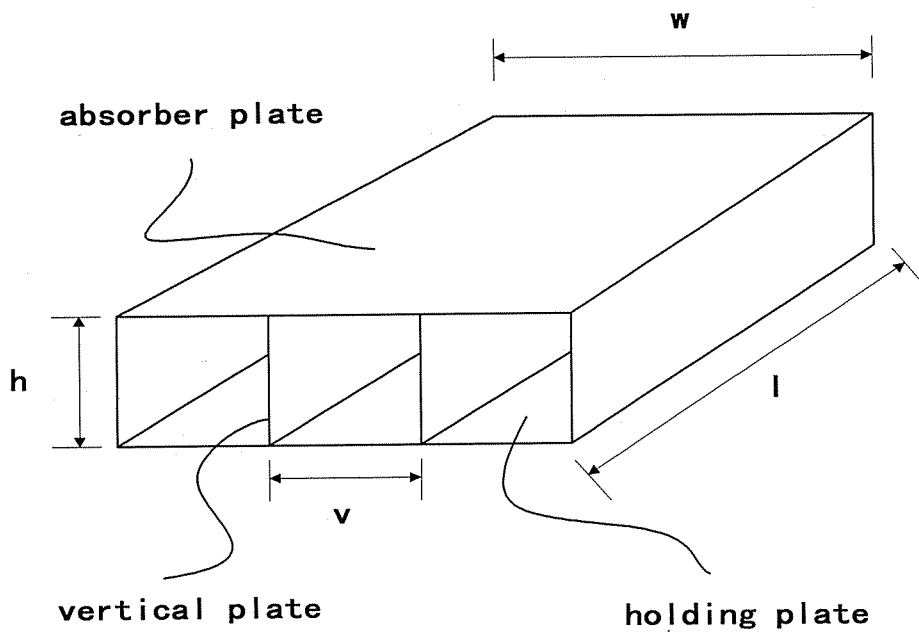


Fig. 2 The plenum of the solar dryer

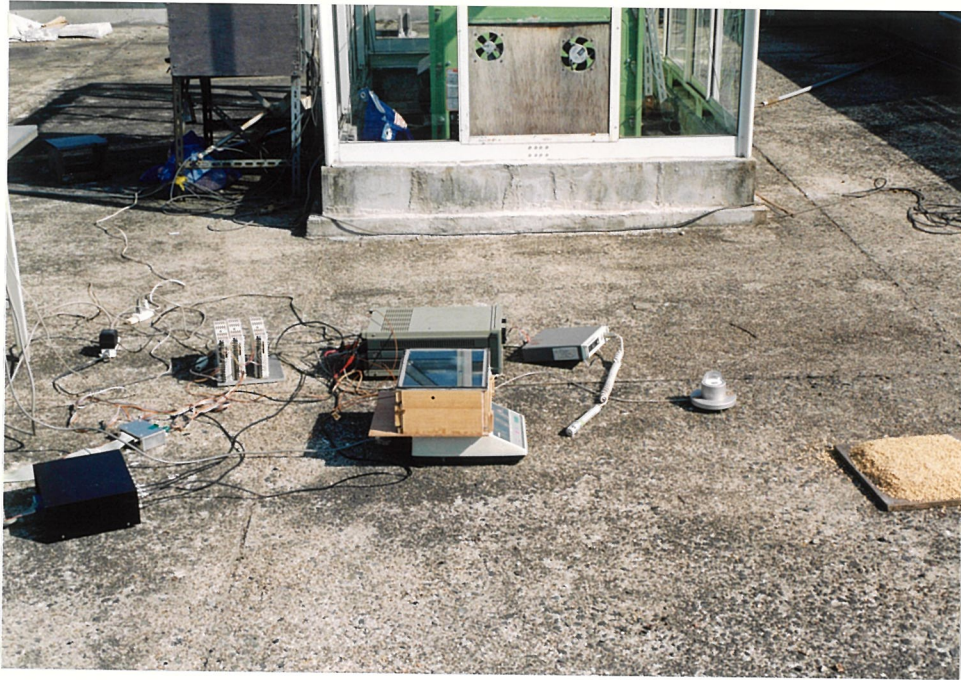


Fig. 3 Photograph of the dryer and the equipment



Fig. 4 Photograph of all the system

3.2. The Neuro-fuzzy control system.

3.2.1. The Fuzzy system.

From the review of literature, 4 input variables to the fuzzy system were determined:

- a. Rice temperature, useful to monitor grain damage. This rice temperature should be kept below 45 °C.
- b. Rice moisture content, useful to monitor drying rate which must be less than 1,5 %/h, and to determine when to stop the drying.
- c. Efficiency, that should be kept as higher as possible, but without overrunning the above constraints..
- d. Air humidity, at the inlet gate of the dryer.

There are other variables that were not considered because they increase the system on size and complexity without adding significant accuracy(i.e. final air humidity, initial air temperature, final air temperature) or because they have a behavior either directly or inversely proportional to any already considered variable, so they can be dealt with together (i.e. delay cost can be assumed to vary inversely as the drying rate, hence the drying rate should not be too low to avoid high delay costs.)

The output variable is the position of a valve in the inlet gate. A position value of 0 degrees corresponds to the gate closed and a position value of 90 degrees corresponds to the gate fully opened. The valve was a vertical sliding plate.

3.2.1.1. The membership function

For the input and output variables we used a bell shaped curve for the membership function. This curve has the equation :

$$f = \frac{(u - m)^2}{S^2}$$

3.2.1.2. The fuzzy sets

All the input variables has 5 fuzzy sets, and the output variable has 6 fuzzy sets.

The values of the fuzzy sets for the variables are:

Input variable: temperature

| Linguistic value | values before training | | values after training | |
|------------------|------------------------|------|-----------------------|-------|
| | m | S | m | S |
| - Cold | 15.0 | 20.0 | 13.41 | 17.86 |
| - Rather cold | 25.0 | 20.0 | 23.00 | 19.90 |
| - Medium | 35.0 | 20.0 | 33.86 | 18.47 |
| - Rather hot | 45.0 | 20.0 | 48.22 | 16.11 |
| - Hot | 55.0 | 20.0 | 54.65 | 20.28 |

Input variable: rice moisture content

| Linguistic value | values before training | | values after training | |
|------------------|------------------------|------|-----------------------|-------|
| | m | S | m | S |
| - Dry | 10.0 | 10.0 | 11.78 | 11.24 |
| - Rather dry | 15.0 | 10.0 | 13.85 | 8.95 |
| - Medium | 20.0 | 10.0 | 25.33 | 9.80 |
| - Rather wet | 25.0 | 10.0 | 27.77 | 5.04 |
| - Wet | 30.0 | 10.0 | 32.67 | 10.34 |

Input variable: efficiency

| Linguistic value | values before training | | values after training | |
|------------------|------------------------|------|-----------------------|-------|
| | m | S | m | S |
| - Bad | 20.0 | 20.0 | 18.23 | 15.84 |
| - Rather bad | 30.0 | 20.0 | 28.75 | 17.78 |
| - Medium | 40.0 | 20.0 | 42.43 | 20.89 |
| - Rather good | 50.0 | 20.0 | 49.92 | 21.19 |
| - Good | 60.0 | 20.0 | 59.89 | 18.33 |

Input variable: air humidity

| Linguistic value | values before training | | values after training | |
|------------------|------------------------|------|-----------------------|-------|
| | m | S | m | S |
| - Low | 30.0 | 20.0 | 29.54 | 17.75 |
| - Rather low | 40.0 | 20.0 | 40.40 | 21.60 |
| - Medium | 50.0 | 20.0 | 54.08 | 18.92 |
| - Rather high | 60.0 | 20.0 | 60.30 | 20.08 |
| - High | 70.0 | 20.0 | 68.94 | 20.87 |

Output variable: gate position

| Linguistic value | values before training | | values after training | |
|------------------|------------------------|------|-----------------------|-------|
| | m | S | m | S |
| - Closed | 0.0 | 36.0 | 0.20 | 37.70 |
| - Almost closed | 18.0 | 36.0 | 17.03 | 35.43 |
| - Rather closed | 36.0 | 36.0 | 37.83 | 35.12 |
| - Rather open | 54.0 | 36.0 | 55.26 | 34.31 |
| - Almost open | 72.0 | 36.0 | 75.35 | 36.56 |
| - Open | 90.0 | 36.0 | 92.98 | 36.78 |

3.2.1.3. The rule base

Expertise for the rule base was obtained from data in the literature and from the tests that were done on experimental models of the dryer.

The rule base has 25 rules, which are shown in the appendix B.

3.2.1.4. The inference engine.

We used fuzzy reasoning of the first type, as the Mandani's minimum fuzzy implication rule.

3.2.1.5. The defuzzification

The centroid method, in which the center of mass of the result is taken as the output crisp value, was used.

3.2.2. The Neural Network.

A fifth layer neural network was selected, with each layer performing as:

- a. First layer, has 4 nodes (one for each input variable).
- b. Second layer, is divided in 4 sections, one for each input variable. Every section has 5 nodes, each node holds the information for one fuzzy subset of the correspondent input variable. Consequently the whole layer has 20 nodes.
- c. Third layer, holds the rulebase, it has 1 node for each rule, therefore it has 25 nodes.
- d. Fourth layer, has 6 nodes, each one has the information for 1 fuzzy subset of the output variable.
- e. Fifth layer, has 1 node, which delivers the final value.

The whole NN has 56 nodes, see fig. 5.

3.2.2.1. The learning constant.

As a large value of the learning constant speeds up the convergence but could result in overshooting, while a smaller value of the learning constant has a complementary effect, [27], a value of 0.1 was chosen.

3.2.2.2. The error

The allowable error in the output value of the NFC system was set to 0.1 degrees, this is the opening angle on the gate.

The neural network works forwards and backwards. In the forward state it calculates an output value, in the backward state, it adjust its weights with a backpropagation algorithm.

3.2.3. The Neuro-fuzzy Control .

The NFC was first trained to tune the parameters in the Fuzzy system. Two parameters were tuned: m (center value of subset) and S (width of subset).

This training was a supervised one, that is after giving some input data to the NFC, it calculated an output value. This was compared with a known desired output value, and according to the error or difference between both values (calculated and desired), the m and S parameters were adjusted through a backpropagation algorithm.

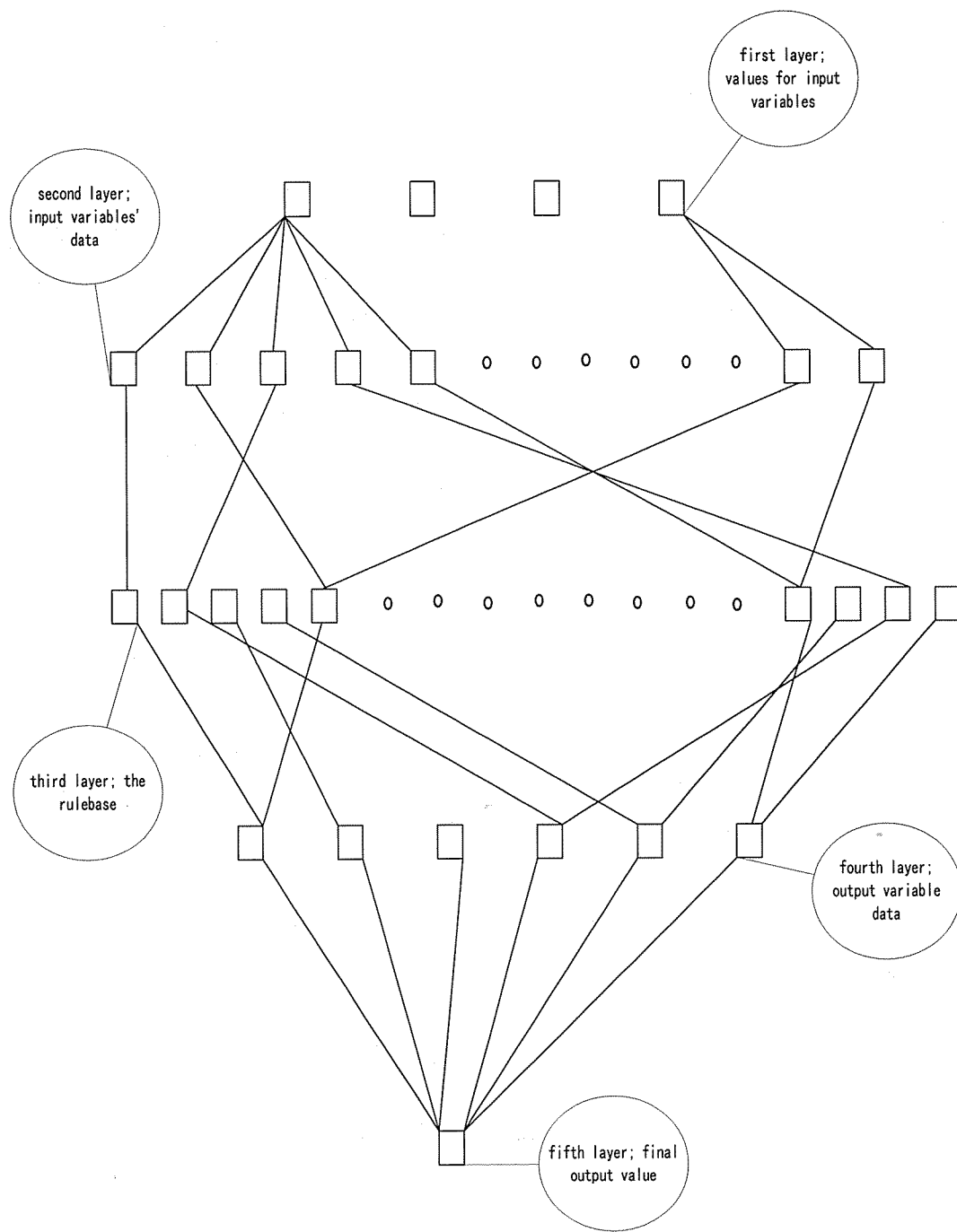


Fig. 5 Structure of the neural network

The developed NFC system is based on a Fuzzy Adaptive Learning Control Network (FALCON) proposed by Lin and Lee to study hybrid structure-parameter learning strategies. It is a feedforward network with 5 layers using backpropagation algorithm, parameter tuning, supervised learning and centroid defuzzification.

The NFC system was trained so that it could adjust optimally the values “m” and “S” of the various fuzzy subsets, 320 training sets of data were used in the training.

The Neuro-fuzzy control system works:

- a. An input value (e.g. temperature 30.0 °C, moisture content of rice 18.75 %, efficiency 35.0%, air humidity 45.5%) is fed into the first layer. This first layer works as a buffering unit, without changing or doing any operation with the input values. Hence, all the links weights on the first layer are equal to 1.
- b. In the second layer, for each input variable, the input value is compared with the stored information of “m” and “S” in order to determine a membership true value for each fuzzy subset. (e.g. if the input value for temperature is 30 °C then the achieved truth value for fuzzy subset “cold” is 0.01, “rathercold” is 0.2, “medium” is 0.4, “ratherhot” is 0.8 and “hot” is 0.6). The same is done with rice moisture content, efficiency and air humidity. As a result, the fuzzification of the data is performed in this layer. The link weights on this layer are considered to be the same as the value of “m” for each node.
- c. In the third layer, it is decided which rules are firing according to the information coming from layer 2 (e.g. if temperature is hot and moisture is low and efficiency is high and airhumidity is medium then the position is semiopen). The link weights in this layer are equal to 1.
- d. In the fourth layer, each fired consequent is compared with the information of the output fuzzy subsets (“m” and “S”), and the truth membership values are determined. After this, for each node, the smaller truth value is chosen. (e.g. is the fuzzy subset of gate position “semiopen” has the truth values 0.7, 0.4, 0.2, 0.5 and 0.7, the true value of this node is 0.2). The link weights in this layer are equal to 1.
- e. In the fifth layer, the defuzzification is performed to obtain the crisp or output value. The centroid method is used. The link weights in this layer are equal to the product of m . S

The algorithm used in the NFC System is shown in the appendix D.

The program to run the algorithm was made in C language. This program is shown in the appendix E.

IV RESULTS AND DISCUSSION

A summary of the results obtained is shown in table 1.

Table 1 Results of the 3 tests in the Neuro-fuzzy controlled solar dryer

| | Date | Ho | Hf | EE. | Temp. | DR | Wo |
|---------|----------|------|-------|-------|-------|-------|--------|
| Test 1 | 97-10-15 | 20.0 | 13.93 | 20.55 | 31.04 | 0.899 | 1327.0 |
| Control | | 20.0 | 16.30 | 13.40 | - | 0.54 | 1380.0 |
| Test 2 | 97-10-16 | 19.6 | 15.90 | 21.57 | 36.31 | 0.77 | 1382.0 |
| Control | | 19.6 | 17.50 | 12.40 | - | 0.43 | 1374.8 |
| Test 3 | 97-10-17 | 19.1 | 15.78 | 23.49 | 27.09 | 0.64 | 1432.9 |
| Control | | 19.1 | 17.1 | 14.0 | - | 0.38 | 1392.6 |

All the data gathered in the 3 tests is shown in the appendix F.

4.1. Solar dryer.

A clear superiority of the solar dryer upon the sun drying (control method) can be observed, see figures 6 and 7.

4.1.1. Energetic efficiency.

The energetic efficiency in the solar dryer has an average value of 22% (considering an energy requirement of 2 MJ/kg H₂O evaporated, as 100% efficient.) The percentage value looks low, but if we consider that the operation of the dryer was constrained by the temperature and drying rate (not higher than 45 °C and 1.5 %/h, respectively), this rather low efficiency is understood.

We have to respect these constraints to assure a low crack ratio and good rice quality.

Were the dryer to work without restrictions, its efficiency would be near 50 % (see results of dryers without control system in the preliminary tests, page 15).

The efficiency of the dryer is similar to the average 7 MJ/kg H₂O of a standard passive solar dryer, on which no limitations of temperature or drying rates are considered.

4.1.2. Temperature.

The temperature in the plenum chamber varied between 22 and 39 °C, values which are below the allowed maximum of 45 °C. Also, the variation of the temperature in the

plenum (important to avoid rice cracking) was smooth thanks to the NFC system. .

4.1.3. Drying rate.

It varied from 1.4 to 0.12 %/h. In accordance with the literature, it can be seen that the drying rate is higher at the initial drying stages and tends to slow down as the drying goes on.

The wide variation of the temperature and drying rate is explained by the varying solar radiation, sudden variations of solar radiation (which is a characteristic of solar energy) means sudden variations of temperature and drying rates inside the dryer. This factor underlines the importance of a control system in order to improve the performance of the solar dryer.

4.1.4. Rice Moisture Content.

In the 3 tests, the target rice moisture content was achieved.

The main problem found in the operation of the solar dryer was the accurate measurement of the rice moisture content. As the quantity of rice inside the plenum was small (on average 1.5 kg) we could not take samples at intervals to determine the moisture content, because if we did the initial drymass weight would vary, introducing error in the calculations.

The used method (weighing the entire dryer over a period of time and comparing the differences in weight) although correct in theory was not working properly on practice. This was due to the fact that as the resolution of the scale was of 0.1 gr, the wind blowing in the test site caused variations of the measured weight and made it difficult to obtain a stable measurement of the actual weight. Sometimes the weight of the dryer "increased" between two readings, due to the wind.

This problem was dealt with in the software. Nevertheless, it is important to point it because it strengthens the need to develop an accurate and easy method to measure the rice moisture content inside the plenum of dryers.

4.1.5. Costs.

The cost of operation of the solar dryer was of 0.06 US\$/kg of dried rice. This cost was achieved considering an annual usage of 60 days, a repair and conservation factor of 10% and a useful life of 15 years. The calculation is shown in the appendix C. As the drying model is small, the calculated cost is very sensitive (i.e. changes of annual usage, repair and conservation costs coefficient, useful life, etc.), nevertheless it helps to have

an idea of the performance of the dryer.

The operating cost depends heavily on the annual usage of the dryer.

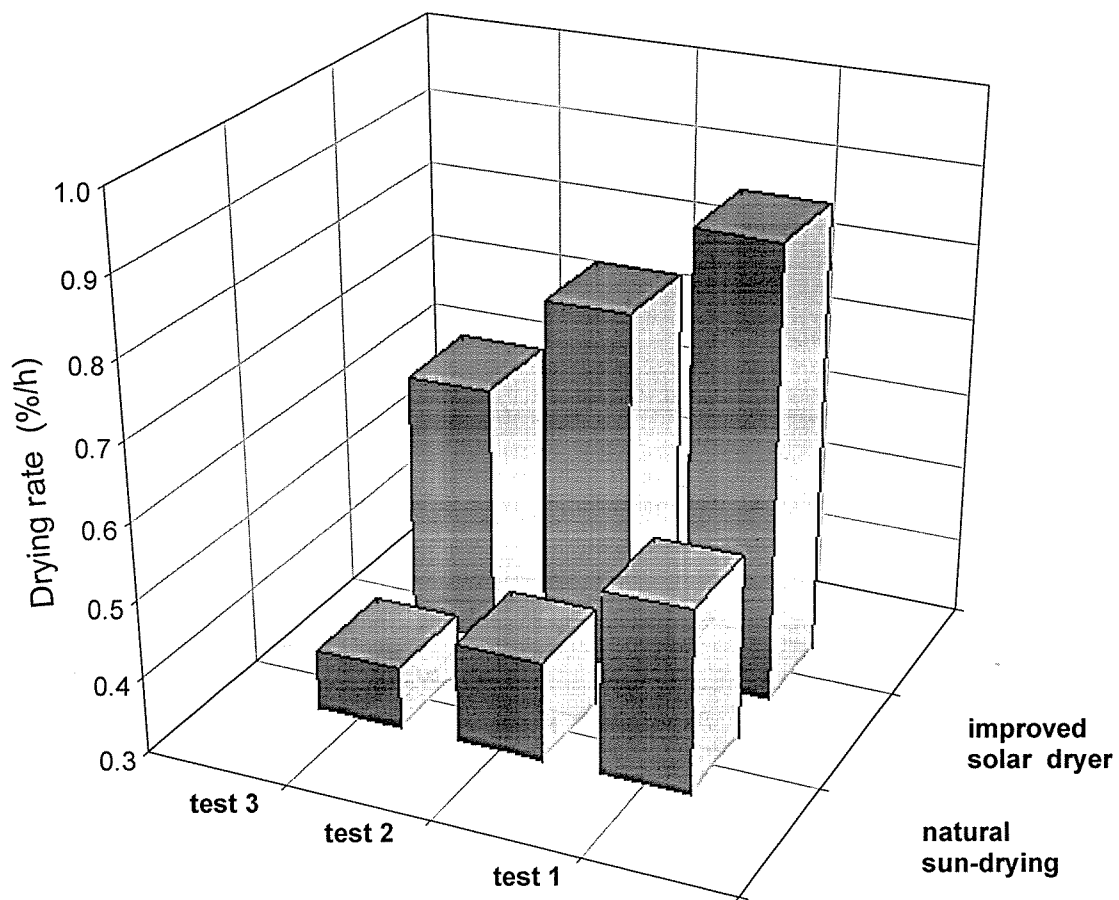


Fig. 6 Comparison of drying rates between the solar dryer and natural sun-drying, for the 3 tests

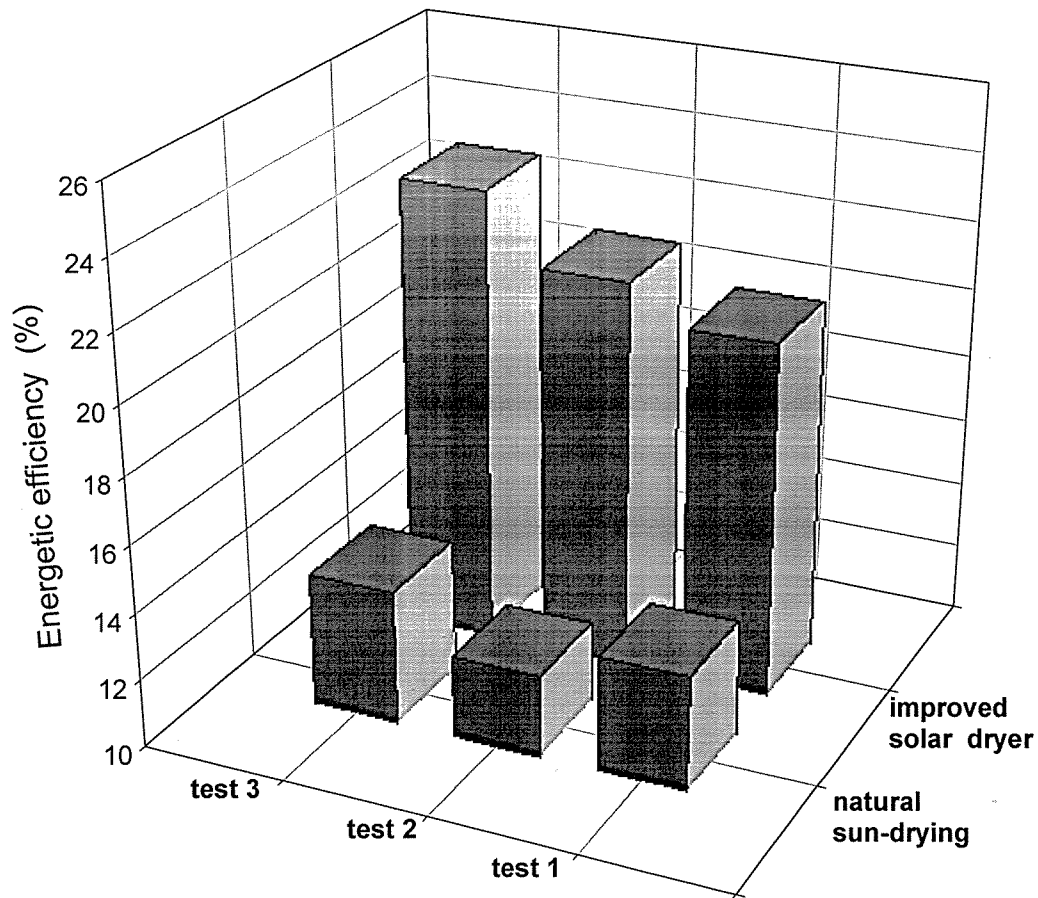


Fig. 7 Energetic efficiency comparison between the solar dryer and natural sun-drying, for the 3 tests

4.2. The Neuro-fuzzy Control System.

The system worked properly and controlled the constraint variables (temperature and drying rate) satisfactorily.

The main problems found on the application of the control system were:

- The generation of the fuzzy rule base, which demands the gathering of data, sometimes unavailable. Also it is rather difficult to estimate the correct amount of required rules.

- The training of the NFCS, which also demands the gathering of training data. This data is sometimes difficult to obtain because, at some stages we did not know which was the best value of the output variable (position of gate) for a given set of input data

The 2 drawbacks pointed above can be softened through the use of an unsupervised NFCS, so we think it is advisable to use this kind of learning instead of the supervised learning we used.

The building of the fuzzy system was much more simpler than the building of the neural network. So if there is enough available knowledge for the rule base, we think the use of a fuzzy control system is better.

5. CONCLUSIONS

- The proposed solar dryer has an average energy requirement of 8 MJ/kg H₂O evaporated. This requirement is rather high, but this is due to the constraints set for temperature and drying rate in the plenum (not higher than 45 °C and 1.5 %/h respectively).
- The temperature and drying rate inside the dryer were kept below the allowable maximum, even though the solar radiation varied. This emphasizes the importance of a control system in a solar dryer.
- The development of a moisture content sensor, which allows direct (real time) and accurate readings is required. Research in this aspect should be done.
- The cost of the dryer was of 0.06 US\$/kg of dried rice, and depended heavily on the annual usage.
- The fuzzy system was easier to build than the neural network. It is recommended to use unsupervised learning instead of supervised learning in order to avoid problems in data gathering.

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VII APPENDIX

APPENDIX A NOMENCLATURE

- t = temperature, °C
k = thermal conductivity, kJ/h.m.°C
0 = time, h
p = density of the material, N/m³
c = specific heat of the material, kJ/N.°C
l = distance in direction of heat flow, m
q = rate of heat transfer, kJ/h
h = heat transfer coefficient, kJ/h.m² . m .°C
t = temperature of the body of the fluid, °C
ts = temperature of the surface, °C
C = a constant value
A = area normal to heat flow, m²
T1 = absolute temperature of body 1, °K
T2 = absolute temperature of body 2, °K
u = input value of the variable
f = membership or truth value of input value "u"
m = center (or mean value) of the bell shaped curve
S = width (or variance) of the bell shaped curve
Ho = initial moisture content of rice, %(w.b.)
Hf = final moisture content of rice, %(w.b.)
DR = drying rate, %/h
EE. = energetic efficiency of the dryer, %
Temp. = temperature of the rice, °C
Wo = initial weight of sample, g
L = length of dryer, 200 mm
W = width of dryer, 200 mm
a = absorber chamber height, 40 mm
f = free air circulation chamber height, 20 mm
b = rice bed depth, 40 mm
d = distance between vertical plates, 25 mm
g = gate height, 15 mm

APPENDIX B

THE RULE BASE

- If tem is cold and moist is dry and eff is bad and airh is low then posit is rather-closed
- If tem is cold and moist is dry and eff is bad and airh is high then posit is almost-closed
- If tem is cold and moist is dry and eff is rather-good and airh is medium then posit is closed
- If tem is cold and moist is dry and eff is good and airh is rather-high then posit is closed
- If tem is cold and moist is rather-dry and eff is good and airh is rather-low then posit is closed
- If tem is cold and moist is medium and eff is good and airh is medium then posit is almost-closed
- If tem is cold and moist is rather-wet and eff is rather-bad and airh is rather-low then posit is rather-closed
- If tem is cold and moist is rather-wet and eff is good and airh is rather-high then posit is almost-closed
- If tem is cold and moist is wet and eff is bad and airh is low then posit is rather-open
- If tem is cold and moist is wet and eff is rather-good and airh is medium then posit is rather-closed
- If tem is rather-cold and moist is dry and eff is rather-good and airh is rather-low then posit is almost-closed
- If tem is rather-cold and moist is dry and eff is good and airh is high then posit is closed
- If tem is rather-cold and moist is medium and eff is rather-good and airh is rather-low then posit is rather-closed
- If tem is rather-cold and moist is wet and eff is bad and airh is low then posit is almost open
- If tem is rather-cold and moist is wet and eff is rather-good and airh is medium then posit is rather-open
- If tem is medium and moist is dry and eff is good and airh is rather-low then posit is almost-closed
- If tem is medium and moist is rather-dry and eff is rather-bad and airh is medium then posit is rather-open
- If tem is medium and moist is wet and eff is bad and airh is rather-high then posit is

almost-open

If tem is rather-hot and moist is dry and eff is rather-good and airh is rather-low then posit is rather closed

If tem is rather-hot and moist is medium and eff is bad and airh is high then posit is almost-open

If tem is rather-hot and moist is rather-wet and eff is good and airh is medium then posit is rather-open

If tem is rather-hot and moist is wet and eff is bad and airh is rather-low then posit is open

If tem is rather-hot and moist is wet and eff is medium and airh is low then posit is almost open

If tem is hot and moist is medium and eff is bad and airh is low then posit is open

If tem is hot and moist is wet and eff is bad and airh is low then posit is open.

APPENDIX C

COST OF OPERATION OF SOLAR DRYER (on US\$)

1. Materials

| | |
|-----------------------------------|-------|
| - copper sheet | 12.00 |
| - wood | 2.00 |
| - glass | 3.00 |
| - others (paint, insulator, etc.) | 8.00 |

Total 25.00

2. Depreciation (15 years) 1.25 \$/year

3. Repair and conservation costs (10% of new value) 2.50 \$/year

4. Total annual costs 3.75 \$/year

5. Dried rice

Considering it dries 1 kg/day, working during 60 days/year, we obtain a drying weight of 60 kg/year.

6. Operating cost (divide 4 by 5) 0.06 \$/kg

APPENDIX D

THE NEURO-FUZZY ALGORITHM

In each node, of each layer, we need to know its input value, in order to calculate its net input value through the integration function, and next its output value through the activation function.

On the algorithm used, the calculations in each layer were performed according to:

1. Forward state

Layer 1

a. Integration function (f)

$$f = u_i$$

u_i = input value to node "i" of first layer

b. Activation function (a)

$$a = f$$

c. Weights

The weights are constant and equal to the unity, 1

Layer 2

a. Integration function

$$f = - (u_i - m_{ij})^2 / S_{ij}^2$$

u_i = input value to node "i" of second layer

m_{ij} = center value of fuzzy subset node "i" (second layer), receiving input from node "j" (first layer).

S_{ij} = width value of fuzzy subset node "i" (second layer) receiving input from node "j" (first layer).

b. Activation function

$$a = e^f$$

c. Weights

The weights are equal to m_{ij}

Layer 3

a. Integration function

$$f = u_i \min$$

$u_i \min$ = minimum value of all inputs to node "i" in third layer.

b. Activation function

$$a = f$$

c. Weights

The weights are constant and equal to unity, 1.

Layer 4

a. Integration function

$$f = \sum_i^n u_i$$

u_i = input to node "i" in fourth layer

b. Activation function

$$a = 1 \text{ if } f > 1, \text{ otherwise } a = f$$

c. Weights

The weights are constant and equal to unity, 1.

Layer 5

a. Integration function

$$f = \sum_j m_{ij} \cdot S_{ij} \cdot u_{ij}$$

m_{ij} = center value of subset fuzzy "j" in fourth layer, connected to output node "i" in fifth layer

S_{ij} = width of subset fuzzy node "j" in fourth layer, connected to output node "i" in fifth layer.

u_{ij} = input to node "i" in fifth layer, from node "j" in fourth layer.

b. Activation function

$$a = f / \sum_j S_{ij} \cdot u_{ij}$$

S_{ij} = width of fuzzy subset node "j" in fourth layer, connected to output node "i" in fifth layer.

u_{ij} = input to node "i" in fifth layer, coming from node "j" in fourth layer.

c. Weights

The weights are equal to the product $m_{ij} \cdot S_{ij}$

BACKWARD MODE

The backward mode is used for the training of the NF. During the training, it adjusts its weights according to the calculated error. It begins at the fifth layer and finish in the first layer, as:

Layer 5

As the weights on layer 5 are equal to $m_{ij} \cdot S_{ij}$, see above; we need to adjust both to diminish the error:

a. The error (E)

$$E = o_d - o_c$$

o_d = desired output value

o_c = NFC calculated output value

b. Adjusting the center value

$$m_{ija} = m_{ij} + n \cdot E \cdot S_{ij} \cdot u_{ij} / \sum_j S_{ij} \cdot u_{ij}$$

m_{ija} = adjusted center value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer.

m_{ij} = previous center value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer

n = learning constant

E = error in layer fifth

S_{ij} = width of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer

u_{ij} = input value received in node "i" of fifth layer, from node "j" in fourth layer.

c. Adjusting the width value

$$S_{ij}^a = S_{ij} + n \cdot E \cdot (m_{ij} \cdot u_{ij} (\sum_j S_{ij} \cdot u_{ij}) - (\sum_j m_{ij} \cdot S_{ij} \cdot u_{ij}) \cdot u_{ij}) / (\sum_j S_{ij} \cdot u_{ij})^2$$

S_{ij}^a = adjusted width value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer.

S_{ij} = previous width value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer.

n = learning constant

E = error in layer fifth

u_{ij} = input value received in node "i" of fifth layer, from node "j" in fourth layer.

m_{ij} = previous center value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer

Layer 4

As the weights in layer 4 are equal to unity, we do not need to adjust them. We need to calculate the error signal in layer 4 as:

a. The error

$$E = (o_d - o_c) \cdot (m_{ij} \cdot S_{ij} (\sum_j S_{ij} \cdot u_{ij}) - (\sum_j m_{ij} \cdot S_{ij} \cdot u_{ij}) S_{ij}) / (\sum_j S_{ij} \cdot u_{ij})^2$$

E = error in layer fourth

o_d = desired output value in layer fifth

o_c = NFC calculated output value in layer fifth

m_{ij} = previous center value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer.

u_{ij} = input value received in node "i" of fifth layer, from node "j" in fourth layer.

S_{ij} = previous width value of fuzzy subset node "j" in fourth layer, connected to node "i" in fifth layer.

Layer 3

In this layer the weights are constant, so we do not need to adjust them. The error is equal to the error in layer 4.

a. The error

$$E = E_4$$

E = error in layer 3

E_4 = error in layer 4

Layer 2

a. The error

$$E_j = \sum_k q_k$$

where

$q_k = -E_3$ if the output value of node "j" in the second layer is the minimum of the kth inputs to the rule node "i" in the third layer. Otherwise $q_k = 0$

The summation above is performed only in the rule nodes in layer third, that are fed by the fuzzy subset node "j" whose error is being calculated, in the second layer.

E_j = error of fuzzy subset node "j" in second layer.

E_3 = error in layer 3

b. Adjusting the center value

$$m_{ij}^a = m_{ij} + n.E_j.e^{u_j}.2(u_j - m_{ij})/(S_{ij})^2$$

m_{ij}^a = adjusted center value of fuzzy subset node "j" in second layer, connected to node "i" in third layer.

m_{ij} = previous center value of fuzzy subset node "j" in second layer, connected to node "i" in third layer.

u_j = input value received in node "j" in second layer.

S_{ij} = previous width value of fuzzy subset node "j" in second layer, connected to node "i" in third layer.

n = learning constant

E_j = error in node "j" in second layer.

c. Adjusting the width value

$$S_{ij}^a = S_{ij} + n.E_j.e^{u_j}.2(u_j - m_{ij})^2/(S_{ij})^3$$

S_{ij}^a = adjusted width value of fuzzy subset node "j" in second layer, connected to node "i" in third layer.

m_{ij} = previous center value of fuzzy subset node "j" in second layer, connected to

node "i" in third layer.

u_j = input value received in node "j" in second layer.

S_{ij} = previous width value of fuzzy subset node "j" in second layer, connected to node "i" in third layer.

n = learning constant

E_j = error in node "j" in second layer.

Layer 1

There is no need to do calculation in this layer, since its weights are constant and equal to unity.

URO-FUZZY PROGRAM

```

#include <stdio.h>
#include <math.h>
#include <dos.h>
#include <stdlib.h>
#include <bios.h>
#include <conio.h>

#define MAXR_2 5 /* number of membership sets for input variables*/
#define MAXC_2 4 /* four values: "m"(medium value), "d"(width of membership set) "f"(input value to node) "a"(output value from node) */
#define MAXR_3 25 /* number of rules in the ruleset */
#define MAXC_3 6 /* six values: firing set of antecedents (4) and "f" and "a" */
#define MAXR_4 6 /* number of membership sets for output variable */
#define MAXC_4 4 /* m, d, f, a and error */

#define OFF 0
#define ON 1

#define ADR 0xD8 /* address for the stepper motor */
#define ADRE 0x00D4 /* address for the analog data input */
#define FOLDER "datos.txt" /* file with data of input, output variables */
#define INTERVAL 60.0 /* time interval between gate settings, seconds */
#define TEMFAC 1.0 /* conversion factor for temperature */
#define RADFAC 1.0 /* conversion factor for solar radiation calculation*/
#define AIRHFAC 1.

float tem; /* value of temperature */
float hum; /* value of humidity */
float eff; /* value of efficiency */
float airh; /* value of air humidity */
float meta; /* target rice humidity */

float SEC_T[MAXR_2][MAXC_2]={{13.4098, 17.8698}, {23.0059, 19.9024}, {33.8673, 18.4706}, {48.2295, 16.1154}, {54.6504, 20.2854}};
/* matrix of data for input variable temperature */
float SEC_H[MAXR_2][MAXC_2]={{11.7839, 11.2453}, {13.8557, 8.9583}, {27.7783, 5.0489}, {25.3338, 9.8010}, {32.6791, 10.3475}};
/* matrix of data for input variable humidity */
float SEC_E[MAXR_2][MAXC_2]={{18.2300, 15.8446}, {28.7586, 17.7835}, {42.4310, 20.8992}, {49.9289, 21.1923}, {59.8959, 18.3303}};
/* matrix of data for input variable efficiency */
float SEC_A[MAXR_2][MAXC_2]={{29.5481, 17.7508}, {40.4010, 21.6084}, {54.0836, 18.9255}, {60.3003, 20.0855}, {68.9478, 20.8719}};
/* data for input variable air humidity */
float THI_L[MAXR_3][MAXC_3]={{0.0, 0.0, 0.0, 0.0}, {0.0, 0.0, 0.0, 4.0}, {0.0, 3.0, 2.0}, {0.0, 0.0, 4.0, 3.0}, {0.0, 1.0, 4.0, 1.0}, {0.0, 2.0, 4.0, 2.0}, {3.0, 1.0, 1.0}, {0.0, 3.0, 4.0, 3.0}, {0.0, 4.0, 0.0, 0.0}, {0.0, 4.0, 3.0, 2.0}, {0.0, 3.0, 1.0}, {1.0, 0.0, 4.0, 4.0}, {1.0, 2.0, 3.0, 1.0}, {1.0, 4.0, 0.0, 0.0}, {4.0, 3.0, 2.0}, {2.0, 0.0, 4.0, 1.0}, {2.0, 2.0, 1.0, 2.0}, {2.0, 4.0, 0.0, 4.0}, {0.0, 3.0, 1.0}, {3.0, 2.0, 0.0, 4.0}, {3.0, 3.0, 4.0, 2.0}, {3.0, 4.0, 0.0, 1.0}, {4.0, 2.0, 0.0, 0.0}, {4.0, 2.0, 0.0, 0.0}, {4.0, 4.0, 0.0, 0.0}};
float CONSEQ_4[MAXR_3]={{2, 1, 0, 0, 1, 2, 1, 3, 2, 1, 0, 2, 4, 3, 1, 3, 4, 2, 4, 3, 5, 4, 5, 5}};
/* data of firing consequents in ruleset */
float FOU_L[MAXR_4][MAXC_4]={{0.2021, 37.7050}, {17.0393, 35.4334}, {37.8315, 228}, {55.2631, 34.3116}, {75.35840, 36.5660}, {92.9888, 36.7872}};
/* data of output variable position */
float FIV_L[2];
/* data of "f" and "a" for result */
signed com_recvsize();
signed com_recv();
com_init();
ana_peso();
analogdata();
PESO_BAL[2]; /* data of weights from scale */
drymass;

*fp; /* pointer to the data file */
marka=0;

/* BEGIN */

printf("Please enter the target rice humidity %n");
scanf("%f", &meta);
printf("Please enter the dry matter weight in grams %n");
scanf("%f", &drymass);
fopen(FOLDER, "w"); /* erasing previous data */
fclose(fp);

ana:
analogdata(0)*TEMFAC;

```



```

um():
eff():
n = analogdata(2)*AIRHFAC;

ntf("Please enter the values of temperature, rice humidity,
iciency and input air humidity ¥n");
if("%f %f %f %f", &tem, &hum, &eff, &airh);
hum>meta || airh>90.0) /*bug debe ser menor que 90.0 */

rrrec(): /* correcting values out of range */

brw_2():
brw_3():
brw_4():
brw_5():
raba():
pto empieza;
se
te_pos():
(hum<=meta)
printf("The rice has been dried to requested humidity of %f ¥n", meta);
se
printf("Stopped by operator");

```

```

ec()

pat *t_ptr=&tem;
pat *h_ptr=&hum;
pat *e_ptr=&eff;
pat *a_ptr=&airh;
if(*t_ptr<SEC_T[0][0])
*t_ptr=SEC_T[0][0];
if(*t_ptr>SEC_T[MAXR_2-1][0])
*t_ptr=SEC_T[MAXR_2-1][0];
if(*h_ptr<SEC_H[0][0])
*h_ptr=SEC_H[0][0];
if(*h_ptr>SEC_H[MAXR_2-1][0])
*h_ptr=SEC_H[MAXR_2-1][0];
if(*e_ptr<SEC_E[0][0])
*e_ptr=SEC_E[0][0];
if(*e_ptr>SEC_E[MAXR_2-1][0])
*e_ptr=SEC_E[MAXR_2-1][0];
if(*a_ptr<SEC_A[0][0])
*a_ptr=SEC_A[0][0];
if(*a_ptr>SEC_A[MAXR_2-1][0])
*a_ptr=SEC_A[MAXR_2-1][0];

```

```

20) /* routine for going forwards in layer 2 */

float mediot=0.0;
float medioh=0.0;
float medioe=0.0;
float medioa=0.0;
int i;
for(i=0; i<MAXR_2; i++)
{
SEC_T[i][2]=-(tem-SEC_T[i][0])*(tem-SEC_T[i][0])/
(SEC_T[i][1]*SEC_T[i][1]);
mediot = SEC_T[i][2];
SEC_T[i][3]=(float)exp(mediot);
SEC_H[i][2]=-(hum-SEC_H[i][0])*(hum-SEC_H[i][0])/
(SEC_H[i][1]*SEC_H[i][1]);
medioh = SEC_H[i][2];
SEC_H[i][3]=(float)exp(medioh);
SEC_E[i][2]=-(eff-SEC_E[i][0])*(eff-SEC_E[i][0])/
(SEC_E[i][1]*SEC_E[i][1]);
medioe = SEC_E[i][2];
SEC_E[i][3]=(float)exp(medioe);
SEC_A[i][2]=-(airh-SEC_A[i][0])*(airh-SEC_A[i][0])/
(SEC_A[i][1]*SEC_A[i][1]);
medioa = SEC_A[i][2];
SEC_A[i][3]=(float)exp(medioa);
}

```

```

0) /* going forwards in layer 3 */

```

```

float mini=0.0;
int n1=0;
int n2=0;
int n3=0;
int n4=0;
int i;

for(i=0;i<MAXR_3;i++)
{
    n1=(int)THI_L[i][0];
    n2=(int)THI_L[i][1];
    n3=(int)THI_L[i][2];
    n4=(int)THI_L[i][3];
    if (SEC_T[n1][3]<=SEC_H[n2][3] && SEC_T[n1][3]<=SEC_E[n3][3]
        && SEC_T[n1][3]<=SEC_A[n4][3])
        mini=SEC_T[n1][3];
    if (SEC_H[n2][3]<SEC_T[n1][3] && SEC_H[n2][3]<=SEC_E[n3][3]
        && SEC_H[n2][3]<=SEC_A[n4][3])
        mini=SEC_H[n2][3];
    if (SEC_E[n3][3]<SEC_T[n1][3] && SEC_E[n3][3]<SEC_H[n2][3]
        && SEC_E[n3][3]<=SEC_A[n4][3])
        mini=SEC_E[n3][3];
    if (SEC_A[n4][3]<SEC_T[n1][3] && SEC_A[n4][3]<SEC_H[n2][3]
        && SEC_A[n4][3]<SEC_E[n3][3])
        mini=SEC_A[n4][3];
    THI_L[i][4]=mini;
}

```

```

4) /* going forwards in layer 4 */

```

```

float q=0.0;
float suma[MAXR_4];
int n=0;
int i;

```

```

for(i=0;i<MAXR_4;i++)
{
    suma[i]=0.0;
}

```

```

for(i=0;i<MAXR_3;i++)
{
    n=CONSEQ_4[i];
    q=THI_L[i][4];
    suma[n]+=q;
}

```

```

for(i=0;i<MAXR_4;i++)
{
    FOU_L[i][2]=suma[i];
    if (suma[i]<1.0)
        FOU_L[i][3]=suma[i];
    else
        FOU_L[i][3]=1.0;
}

```

```

5) /* going forwards in layer 5 */

```

```

float divisor=0.0;
float limi=0.0; /* checking too low or too high angles */
int i,j,k;
int speed=500;
int angle,medio;

```

```

FIV_L[0]=0.0;
for(i=0;i<MAXR_4;i++)
{
    FIV_L[0] += FOU_L[i][0]*FOU_L[i][1]*FOU_L[i][3];
    divisor += FOU_L[i][1]*FOU_L[i][3];
}

```

```

limi=FIV_L[0]/divisor;
if (limi<0.0)
    limi=0.0;
if (limi>90.0)
    limi=90.0;

```

```

if (marka==0)
{
    FIV_L[1]=0.0;
    marka = 1;
}

```

```

/* moving the stepper */
medio=(int)(limi-FIV_L[1]);

```

```

angle=abs(medio);
outportb(ADR+7, 0x0080);
for(i=0; i<angle; i++)
{
for(j=0; j<speed; j++)
{
if(medio>0)
outportb(ADR+1, 0x02);
else
outportb(ADR+1, 0x10);
}
for(k=0; k<speed; k++)
outportb(ADR+1, 0x00);
}
FIV_L[1]=limi;

/* setting the gate to initial position */
int angle;
int speed=500;
int i, j, k;
outportb(ADR+7, 0x0080);
angle=(int)FIV_L[1];
for(i=0; i<angle; i++)
{
for(j=0; j<speed; j++)
outportb(ADR+1, 0x10);
for(k=0; k<speed; k++)
outportb(ADR+1, 0x00);
}

/* writing the data to a file */
fp=fopen(FOLDER, "a");
printf(fp, "%d %d %d %d %d %d\n", (int)tem, (int)hum, (int)eff, (int)airh,
(int)FIV_L[1]);
fclose(fp);

float ana_peso() /* obtaining the weight from the scale */
unsigned char buf[300], sstr[80];
int ch, rch, send, i, n, j;
com_init(buf);
float senpeso;
int sca_lee[];

ch = com_recv();
while(rch=48 || rch<=57)
{
sca_lee[j]=rch;
j++;
}
while(rch !=0x0d);
senpeso=(sca_lee[0]-48)*10000+(sca_lee[1]-48)*1000+(sca_lee[2]-48)*100+
(sca_lee[3]-48)*10+(sca_lee[4]-48)+(sca_lee[5]-48)*0.1;
return senpeso;

com_init(unsigned char *buf)
/* INIT cint;
int cmd = 1;
int transfer = 0x06;
int mode_inf = 0x5e;
int cmd_inf = 0x37;
int recv_buf = buf;
int recv_siz = 256;
int time_snd = 0x10;
int time_rcv = 0x0f;
com_init(&cint);
while(cint.stus!=0) printf("init_stus=%02x.\n", cint.stus);

return com_recvsize()

/* INFO cinf;
int cmd = 2;
com_init(&cinf);
while(cinf.stus!=0) printf("recvsize_stus=%02x.\n", cinf.stus);
return cinf.data_siz;

```

```

igned com_recv()

OH_INFO cinf;
cinf.cmd = 4;
os98com(&cinf);
if(cinf.stus!=0) printf("recv_stus=%02x.\n", cinf.stus);
return cinf.data;
*/

analogdata(ch)
ch;
{
int regCheck;
int raw_sen;
float ssread;

outportb(ADRE, ch);
regCheck = 0x0000;
do{regCheck = inport(ADRE+1);
}while((regCheck & (0x80))==0);
raw_sen=inportb(ADRE+0)+(inportb(ADRE+1)&(0x0f))*256;
/* conversion of data from voltage to value */
ssread=((10.0/4095.0)*raw_sen);
return ssread;
}

m()

oat peso;

(marka==0)
{
PESO_BAL[0] = ana_peso();
PESO_BAL[1] = PESO_BAL[0];
}

se
{
peso = ana_peso();
hum = (peso - drymass)*100.0/peso;
PESO_BAL[0] = PESO_BAL[1];
PESO_BAL[1] = peso;
}

ff()

at rad;
at evapwat;
at tasa;
at difpeso;

marka==0)
eff=50.0;

rad=analogdata(1)*RADFAC;
difpeso = PESO_BAL[0] - PESO_BAL[1];
if(difpeso != 0.0)
{
tasa = (rad*0.09*INTERVAL)/(PESO_BAL[0]-PESO_BAL[1]);
/* considering 2 Joules/gr of evaporated water as 100% efficiency*/
eff = 2.0*100.0/tasa;
}
else
{
eff = 0.0;
}

```

APPENDIX F

DATA OF THE TESTS

Wednesday October 15th

| Temp. (C) | Moisture (% wb) | Air Hum. (%) | Radiation (mV) | Radiation (kW/m ²) | Efficiency (%) | Gate Angl (degrees) | Dryingrate (%/h) |
|--------------|--------------------|-----------------|-------------------|-----------------------------------|-------------------|------------------------|---------------------|
| 22.6 | 20.00 | 45.17 | 43.37 | 619.57 | 50.00 | 24.1 | 2.16 |
| 22.4 | 19.82 | 45.93 | 43.42 | 620.29 | 42.79 | 35.4 | 1.08 |
| 21.5 | 19.73 | 46.31 | 43.14 | 616.29 | 21.53 | 47.4 | 1.20 |
| 22.4 | 19.63 | 45.98 | 42.87 | 612.43 | 24.08 | 48.2 | 1.08 |
| 23.1 | 19.54 | 45.83 | 42.77 | 611.00 | 21.72 | 46.3 | 0.96 |
| 23.2 | 19.46 | 45.68 | 43.97 | 628.14 | 18.78 | 40.2 | 0.96 |
| 23.1 | 19.38 | 45.45 | 43.39 | 619.86 | 19.03 | 36.8 | 1.08 |
| 24.4 | 19.29 | 43.50 | 43.37 | 619.57 | 21.42 | 45.4 | 0.96 |
| 26.8 | 19.21 | 40.00 | 44.36 | 633.71 | 18.61 | 45.8 | 1.44 |
| 27.9 | 19.09 | 38.72 | 43.52 | 621.71 | 28.46 | 42.7 | 1.32 |
| 29.2 | 18.98 | 36.57 | 43.20 | 617.14 | 26.28 | 34.4 | 1.44 |
| 30.6 | 18.86 | 35.82 | 43.57 | 622.43 | 28.43 | 52.1 | 1.32 |
| 30.7 | 18.75 | 33.15 | 41.66 | 595.14 | 27.25 | 52.1 | 1.08 |
| 30.8 | 18.66 | 34.46 | 42.86 | 612.29 | 21.67 | 37.6 | 1.44 |
| 30.8 | 18.54 | 33.35 | 42.09 | 601.29 | 29.43 | 40.9 | 1.44 |
| 30.0 | 18.42 | 33.45 | 42.09 | 601.29 | 29.43 | 40.5 | 0.84 |
| 30.6 | 18.35 | 33.45 | 42.41 | 605.86 | 17.04 | 50.6 | 1.08 |
| 30.8 | 18.26 | 31.82 | 42.61 | 608.71 | 21.80 | 47.4 | 0.84 |
| 31.2 | 18.19 | 31.49 | 43.06 | 615.14 | 16.78 | 50.2 | 1.44 |
| 32.9 | 18.07 | 30.41 | 42.72 | 610.29 | 28.99 | 41.3 | 1.80 |
| 32.4 | 17.92 | 29.81 | 42.26 | 603.71 | 36.63 | 48.9 | 1.20 |
| 33.2 | 17.82 | 29.71 | 42.15 | 602.14 | 24.49 | 44.2 | 1.08 |
| 34.0 | 17.73 | 29.33 | 43.04 | 614.86 | 21.58 | 49.3 | 1.20 |
| 33.5 | 17.63 | 29.10 | 42.76 | 610.86 | 24.14 | 46.1 | 1.20 |
| 34.0 | 17.53 | 29.33 | 43.26 | 618.00 | 23.86 | 49.9 | 0.96 |
| 32.8 | 17.45 | 29.53 | 42.87 | 612.43 | 19.26 | 36.8 | 0.96 |
| 33.7 | 17.37 | 29.50 | 42.93 | 613.29 | 19.23 | 49.1 | 1.08 |
| 33.7 | 17.28 | 27.82 | 42.78 | 611.14 | 21.71 | 37.6 | 1.32 |
| 34.3 | 17.17 | 27.29 | 43.52 | 621.71 | 26.09 | 48.7 | 1.20 |
| 33.6 | 17.07 | 27.42 | 43.66 | 623.71 | 23.64 | 30.6 | 1.20 |
| 32.4 | 16.97 | 27.49 | 45.56 | 650.86 | 22.65 | 42.6 | 0.96 |
| 31.3 | 16.89 | 27.24 | 45.35 | 647.86 | 18.21 | 46.4 | 1.20 |
| 29.7 | 16.79 | 28.04 | 45.26 | 646.57 | 22.80 | 41.9 | 1.80 |
| 28.7 | 16.64 | 30.04 | 46.65 | 666.43 | 33.19 | 34.4 | 1.08 |
| 27.7 | 16.55 | 32.04 | 45.60 | 651.43 | 20.37 | 43.5 | 0.84 |
| 27.7 | 16.48 | 31.99 | 43.40 | 620.00 | 16.65 | 45.0 | 1.92 |
| 28.7 | 16.32 | 31.32 | 44.56 | 636.57 | 37.06 | 31.7 | 1.08 |
| 29.7 | 16.23 | 36.19 | 42.70 | 610.00 | 21.75 | 44.5 | 1.08 |
| 29.7 | 16.14 | 36.52 | 41.23 | 589.00 | 22.53 | 28.5 | 0.96 |
| 29.6 | 16.06 | 36.97 | 40.20 | 574.29 | 20.54 | 43.7 | 1.68 |
| 30.1 | 15.92 | 37.15 | 38.70 | 552.86 | 37.34 | 28.3 | 0.48 |
| 30.1 | 15.88 | 38.91 | 36.00 | 514.29 | 11.47 | 42.8 | 1.08 |
| 30.3 | 15.79 | 37.68 | 37.56 | 536.57 | 24.73 | 37.0 | 1.80 |
| 30.7 | 15.64 | 39.04 | 34.80 | 497.14 | 44.49 | 27.3 | 0.60 |
| 30.7 | 15.59 | 39.61 | 37.85 | 540.71 | 13.63 | 41.9 | 0.72 |

| Temp. (C) | Moisture (% wb) | Air Hum. (%) | Radiation (mV) | Radiation (kW/m ²) | Efficiency (%) | Gate Angl (degrees) | Dryingrate (%/h) |
|--------------|--------------------|-----------------|-------------------|-----------------------------------|-------------------|------------------------|---------------------|
| 30.7 | 15.53 | 39.44 | 39.45 | 563.57 | 15.70 | 41.8 | 0.60 |
| 31.1 | 15.48 | 39.59 | 32.87 | 469.57 | 15.70 | 41.7 | 0.60 |
| 31.8 | 15.43 | 40.67 | 31.04 | 443.43 | 16.63 | 41.3 | 0.48 |
| 31.4 | 15.39 | 42.03 | 34.78 | 496.86 | 11.87 | 40.8 | 0.72 |
| 31.6 | 15.33 | 42.18 | 35.21 | 503.00 | 17.59 | 40.6 | 0.72 |
| 32.0 | 15.27 | 41.38 | 32.62 | 466.00 | 18.98 | 40.7 | 1.08 |
| 32.5 | 15.18 | 41.75 | 33.45 | 477.86 | 27.77 | 28.1 | 0.72 |
| 32.1 | 15.12 | 41.25 | 33.76 | 482.29 | 18.34 | 40.2 | 0.84 |
| 32.2 | 15.05 | 42.03 | 33.51 | 478.71 | 21.56 | 37.2 | 0.96 |
| 32.5 | 14.97 | 42.89 | 32.01 | 457.29 | 25.79 | 33.0 | 0.60 |
| 33.3 | 14.92 | 43.46 | 34.81 | 497.29 | 14.82 | 39.1 | 0.48 |
| 33.7 | 14.88 | 42.43 | 33.39 | 477.00 | 12.36 | 39.4 | 0.60 |
| 33.1 | 14.83 | 43.69 | 32.61 | 465.86 | 15.83 | 38.8 | 0.60 |
| 33.6 | 14.78 | 42.56 | 34.29 | 489.86 | 15.05 | 39.1 | 0.60 |
| 32.9 | 14.73 | 43.01 | 31.20 | 445.71 | 16.54 | 38.7 | 0.72 |
| 33.2 | 14.67 | 42.63 | 30.47 | 435.29 | 20.32 | 38.8 | 0.72 |
| 32.0 | 14.61 | 41.78 | 30.21 | 431.57 | 20.50 | 39.0 | 0.60 |
| 32.4 | 14.56 | 42.18 | 31.02 | 443.14 | 16.64 | 25.4 | 0.48 |
| 32.1 | 14.52 | 44.49 | 28.03 | 400.43 | 14.73 | 37.6 | 0.48 |
| 32.4 | 14.48 | 44.60 | 26.40 | 377.14 | 15.64 | 37.5 | 0.36 |
| 32.2 | 14.45 | 43.61 | 29.79 | 425.57 | 10.39 | 37.8 | 0.96 |
| 32.5 | 14.37 | 43.09 | 31.56 | 450.86 | 26.16 | 31.2 | 0.36 |
| 32.1 | 14.34 | 42.23 | 31.67 | 452.43 | 9.78 | 37.9 | 0.60 |
| 32.0 | 14.29 | 43.46 | 29.45 | 420.71 | 17.52 | 37.4 | 0.36 |
| 32.8 | 14.26 | 42.61 | 23.85 | 340.71 | 12.98 | 37.6 | 0.48 |
| 33.2 | 14.22 | 42.71 | 29.03 | 414.71 | 14.22 | 37.5 | 0.48 |
| 32.6 | 14.18 | 43.44 | 26.71 | 381.57 | 15.46 | 37.1 | 0.36 |
| 33.4 | 14.15 | 42.94 | 26.44 | 377.71 | 11.71 | 37.2 | 0.36 |
| 33.9 | 14.12 | 42.38 | 25.94 | 370.57 | 11.94 | 37.3 | 0.36 |
| 34.1 | 14.09 | 41.85 | 25.38 | 362.57 | 12.20 | 37.4 | 0.48 |
| 34.6 | 14.05 | 41.25 | 26.85 | 383.57 | 15.38 | 37.5 | 0.48 |
| 34.6 | 14.01 | 41.98 | 24.07 | 343.86 | 17.15 | 37.1 | 0.24 |
| 34.6 | 13.99 | 41.80 | 25.69 | 367.00 | 8.04 | 37.1 | 0.24 |
| 34.8 | 13.97 | 41.30 | 24.21 | 345.86 | 8.53 | 37.2 | 0.24 |
| 34.9 | 13.95 | 41.20 | 21.20 | 302.86 | 9.74 | 37.2 | 0.12 |
| 34.9 | 13.94 | 42.31 | 16.30 | 232.86 | 6.33 | 36.8 | 0.12 |
| 34.5 | 13.93 | 31.83 | 23.86 | 340.86 | 4.33 | 0.0 | |

Average 31.0 38.17 36.69 524.08 20.56 39.4 0.90

* The value of radiation in column 4 is in milivolts mV

*The values corresponds to 5 minute intervals

Thursday October 16th

| Temp. (C) | Moisture (% wb) | Air Hum. (%) | Radiation (mV) | Radiation (kW/m2) | Efficiency (%) | Gate Angl (degrees) | Dryingrate (%/h) |
|--------------|--------------------|-----------------|-------------------|----------------------|-------------------|------------------------|---------------------|
| 37.0 | 19.60 | 30.38 | 46.03 | 657.57 | 50.00 | 32.1 | 2.16 |
| 38.3 | 19.42 | 30.69 | 46.53 | 664.71 | 41.58 | 52.6 | 0.96 |
| 38.0 | 19.34 | 30.18 | 46.25 | 660.71 | 18.59 | 53.8 | 0.96 |
| 37.4 | 19.26 | 30.41 | 39.45 | 563.57 | 21.80 | 55.6 | 0.96 |
| 36.7 | 19.18 | 30.51 | 43.37 | 619.57 | 19.83 | 56.1 | 1.08 |
| 37.9 | 19.09 | 29.48 | 33.55 | 479.29 | 28.83 | 38.0 | 1.08 |
| 38.6 | 19.00 | 30.06 | 44.27 | 632.43 | 21.85 | 47.8 | 0.96 |
| 38.6 | 18.92 | 28.52 | 36.92 | 527.43 | 23.29 | 56.0 | 0.36 |
| 37.6 | 18.89 | 28.05 | 40.94 | 584.86 | 7.88 | 39.8 | 1.08 |
| 36.7 | 18.80 | 28.22 | 28.99 | 414.14 | 33.37 | 43.2 | 1.08 |
| 35.8 | 18.71 | 29.23 | 34.74 | 496.29 | 27.85 | 49.8 | 1.08 |
| 36.2 | 18.62 | 29.25 | 33.66 | 480.86 | 28.74 | 29.9 | 0.96 |
| 36.1 | 18.54 | 29.50 | 31.28 | 446.86 | 27.49 | 37.9 | 1.08 |
| 35.9 | 18.45 | 29.03 | 36.32 | 518.86 | 26.64 | 38.0 | 1.08 |
| 34.7 | 18.36 | 28.72 | 37.53 | 536.14 | 25.78 | 36.7 | 1.08 |
| 33.6 | 18.27 | 27.97 | 35.18 | 502.57 | 27.50 | 40.3 | 0.96 |
| 35.0 | 18.19 | 27.97 | 30.23 | 431.86 | 28.45 | 51.4 | 1.20 |
| 34.5 | 18.09 | 28.55 | 28.08 | 401.14 | 38.28 | 40.7 | 0.96 |
| 36.0 | 18.01 | 27.57 | 34.70 | 495.71 | 24.78 | 50.6 | 0.96 |
| 35.9 | 17.93 | 28.25 | 27.35 | 390.71 | 31.44 | 26.5 | 1.08 |
| 36.2 | 17.84 | 28.05 | 30.38 | 434.00 | 31.84 | 50.4 | 0.84 |
| 36.8 | 17.77 | 28.10 | 34.54 | 493.43 | 21.78 | 35.3 | 0.84 |
| 37.5 | 17.70 | 28.37 | 40.79 | 582.71 | 18.45 | 50.4 | 0.96 |
| 37.5 | 17.62 | 28.15 | 45.10 | 644.29 | 19.07 | 38.0 | 0.12 |
| 37.8 | 17.61 | 27.69 | 45.82 | 654.57 | 2.35 | 42.1 | 0.96 |
| 37.6 | 17.53 | 27.62 | 33.57 | 479.57 | 25.62 | 41.9 | 1.08 |
| 36.9 | 17.44 | 26.56 | 34.24 | 489.14 | 28.25 | 34.3 | 1.08 |
| 37.6 | 17.35 | 26.84 | 41.29 | 589.86 | 23.43 | 40.9 | 0.84 |
| 38.9 | 17.28 | 26.81 | 34.11 | 487.29 | 22.06 | 39.3 | 1.08 |
| 37.8 | 17.19 | 26.84 | 17.37 | 248.14 | 55.69 | 34.4 | 0.60 |
| 37.3 | 17.14 | 27.59 | 19.26 | 275.14 | 27.90 | 26.2 | 0.60 |
| 38.2 | 17.09 | 27.64 | 25.14 | 359.14 | 21.38 | 30.5 | 0.84 |
| 37.1 | 17.02 | 28.98 | 31.84 | 454.86 | 23.63 | 33.1 | 0.72 |
| 37.0 | 16.96 | 28.88 | 37.07 | 529.57 | 17.40 | 46.7 | 0.36 |
| 35.6 | 16.93 | 29.08 | 39.83 | 569.00 | 8.10 | 46.0 | 0.72 |
| 36.0 | 16.87 | 29.58 | 32.39 | 462.71 | 19.91 | 46.0 | 0.60 |
| 36.8 | 16.82 | 28.47 | 32.83 | 469.00 | 16.37 | 46.1 | 0.96 |
| 37.1 | 16.74 | 29.15 | 40.66 | 580.86 | 21.15 | 46.1 | 0.60 |
| 36.2 | 16.69 | 27.69 | 39.58 | 565.43 | 13.58 | 45.6 | 0.84 |
| 36.7 | 16.62 | 27.79 | 37.12 | 530.29 | 20.27 | 45.6 | 0.72 |
| 37.3 | 16.56 | 28.27 | 31.16 | 445.14 | 20.70 | 45.6 | 0.36 |
| 37.7 | 16.53 | 28.42 | 37.22 | 531.71 | 8.66 | 45.6 | 0.96 |
| 36.4 | 16.45 | 28.22 | 30.89 | 441.29 | 27.84 | 45.1 | 0.72 |
| 36.5 | 16.39 | 30.28 | 23.66 | 338.00 | 27.26 | 31.3 | 0.48 |
| 34.6 | 16.35 | 30.23 | 33.55 | 479.29 | 12.82 | 39.4 | 0.48 |
| 34.7 | 16.31 | 28.32 | 32.72 | 467.43 | 13.14 | 36.6 | 0.72 |
| 35.5 | 16.25 | 27.16 | 32.87 | 469.57 | 19.62 | 38.6 | 0.84 |

| Temp. (C) | Moisture (% wb) | Air Hum. (%) | Radiation (mV) | Radiation (kW/m ²) | Efficiency (%) | Gate Angl (degrees) | Dryingrate (%/h) |
|--------------|--------------------|-----------------|-------------------|-----------------------------------|-------------------|------------------------|---------------------|
| 36.6 | 16.18 | 28.37 | 27.70 | 395.71 | 27.16 | 44.1 | 0.60 |
| 34.9 | 16.13 | 28.17 | 33.06 | 472.29 | 16.26 | 43.5 | 0.48 |
| 35.3 | 16.09 | 27.97 | 31.81 | 454.43 | 13.52 | 37.7 | 0.48 |
| 36.0 | 16.05 | 27.34 | 29.85 | 426.43 | 14.40 | 39.4 | 0.48 |
| 34.8 | 16.01 | 26.14 | 30.01 | 428.71 | 14.33 | 43.1 | 0.36 |
| 33.8 | 15.98 | 28.13 | 29.54 | 422.00 | 10.92 | 42.7 | 0.24 |
| 34.3 | 15.96 | 29.22 | 29.72 | 424.57 | 7.23 | 42.8 | 0.12 |
| 33.6 | 15.95 | 29.01 | 25.18 | 359.71 | 4.27 | 42.5 | 0.12 |
| 34.1 | 15.94 | 27.04 | 24.14 | 344.86 | 4.45 | 42.5 | 0.24 |
| 33.9 | 15.92 | 28.28 | 26.09 | 372.71 | 8.24 | 42.5 | 0.24 |
| 33.3 | 15.90 | 29.16 | 25.88 | 369.71 | 8.31 | 0.0 | 0.24 |

| | | | | | | | | |
|---------|------|--|-------|--|--------|-------|------|------|
| Average | 36.3 | | 28.49 | | 483.58 | 21.57 | 41.4 | 0.78 |
|---------|------|--|-------|--|--------|-------|------|------|

* The value of radiation in column 4 is in millivolts mV

* The values correspond to 5 minute intervals

Friday October 17th

| Temp. (C) | Moisture (% wb) | Air hum. (%) | Radiation (mV) | Radiation (kW/m2) | Efficiency (%) | Gate Angl (degrees) | Dryingrate (%/h) |
|--------------|--------------------|-----------------|-------------------|----------------------|-------------------|------------------------|---------------------|
| 26.7 | 19.10 | 28.37 | 42.58 | 608.29 | 50.00 | 26.4 | 2.04 |
| 28.6 | 18.93 | 32.32 | 16.32 | 233.14 | 35.99 | 38.4 | 0.72 |
| 31.6 | 18.87 | 50.48 | 14.02 | 200.29 | 33.14 | 41.9 | 1.44 |
| 31.8 | 18.75 | 50.20 | 14.19 | 202.71 | 77.16 | 24.6 | 1.08 |
| 31.5 | 18.66 | 49.20 | 14.60 | 208.57 | 57.17 | 24.6 | 0.96 |
| 27.0 | 18.58 | 49.02 | 10.38 | 148.29 | 49.39 | 25.3 | 1.44 |
| 23.7 | 18.46 | 49.17 | 10.87 | 155.29 | 104.21 | 19.1 | 0.84 |
| 25.2 | 18.39 | 48.37 | 10.26 | 146.57 | 58.05 | 20.5 | 1.08 |
| 31.4 | 18.30 | 47.99 | 9.32 | 133.14 | 79.07 | 23.7 | 1.08 |
| 32.2 | 18.21 | 48.75 | 34.36 | 490.86 | 87.05 | 24.0 | 0.72 |
| 32.9 | 18.15 | 48.62 | 19.73 | 281.86 | 15.74 | 48.3 | 1.32 |
| 32.8 | 18.04 | 49.20 | 26.37 | 376.71 | 50.26 | 26.6 | 1.08 |
| 32.9 | 17.95 | 50.25 | 41.16 | 588.00 | 30.77 | 37.2 | 0.72 |
| 32.4 | 17.89 | 49.65 | 40.92 | 584.57 | 13.14 | 47.1 | 1.08 |
| 33.1 | 17.80 | 49.73 | 36.86 | 526.57 | 19.83 | 46.1 | 0.96 |
| 27.7 | 17.72 | 39.21 | 43.39 | 619.86 | 19.56 | 47.5 | 0.84 |
| 28.1 | 17.65 | 39.26 | 42.08 | 601.14 | 14.54 | 48.2 | 1.20 |
| 26.1 | 17.55 | 38.91 | 42.59 | 608.43 | 21.42 | 45.4 | 0.96 |
| 24.8 | 17.47 | 38.99 | 43.22 | 617.43 | 16.93 | 47.7 | 0.84 |
| 27.3 | 17.40 | 38.68 | 43.30 | 618.57 | 14.60 | 47.5 | 0.60 |
| 25.1 | 17.35 | 38.81 | 21.21 | 303.00 | 10.41 | 47.3 | 0.60 |
| 27.3 | 17.30 | 37.83 | 27.36 | 390.86 | 21.25 | 44.9 | 0.72 |
| 26.0 | 17.24 | 40.14 | 41.98 | 599.71 | 19.77 | 45.5 | 0.48 |
| 27.1 | 17.20 | 37.33 | 21.46 | 306.57 | 8.59 | 47.1 | 0.72 |
| 28.8 | 17.14 | 36.67 | 17.92 | 256.00 | 25.20 | 40.5 | 0.24 |
| 24.4 | 17.12 | 35.99 | 28.19 | 402.71 | 10.06 | 46.9 | 0.48 |
| 24.9 | 17.08 | 35.84 | 14.02 | 200.29 | 12.79 | 46.8 | 0.60 |
| 27.4 | 17.03 | 34.81 | 39.34 | 562.00 | 32.15 | 33.9 | 0.60 |
| 30.3 | 16.98 | 34.01 | 15.21 | 217.29 | 11.46 | 46.5 | 0.60 |
| 29.6 | 16.93 | 30.16 | 31.97 | 456.71 | 29.63 | 37.5 | 0.72 |
| 27.9 | 16.87 | 30.54 | 32.41 | 463.00 | 16.92 | 46.1 | 0.36 |
| 28.1 | 16.84 | 29.23 | 31.67 | 452.43 | 8.34 | 46.1 | 0.60 |
| 24.2 | 16.79 | 28.80 | 31.64 | 452.00 | 14.23 | 45.9 | 0.60 |
| 27.7 | 16.74 | 33.96 | 42.08 | 601.14 | 14.25 | 45.8 | 0.60 |
| 27.1 | 16.69 | 33.53 | 24.55 | 350.71 | 10.71 | 45.6 | 0.48 |
| 26.3 | 16.65 | 33.63 | 26.01 | 371.57 | 14.69 | 45.5 | 0.60 |
| 28.0 | 16.60 | 33.98 | 43.50 | 621.43 | 17.33 | 45.4 | 0.72 |
| 24.2 | 16.54 | 28.80 | 31.64 | 452.00 | 12.43 | 45.2 | 0.36 |
| 27.0 | 16.51 | 30.13 | 25.42 | 363.14 | 8.55 | 45.1 | 0.72 |
| 26.7 | 16.45 | 30.36 | 24.82 | 354.57 | 21.28 | 42.3 | 0.60 |
| 26.7 | 16.40 | 30.31 | 24.15 | 345.00 | 18.16 | 44.8 | 0.36 |
| 26.9 | 16.37 | 30.21 | 23.70 | 338.57 | 11.20 | 44.7 | 0.36 |
| 25.1 | 16.34 | 30.08 | 21.77 | 311.00 | 11.41 | 44.6 | 0.60 |
| 24.4 | 16.29 | 30.18 | 23.76 | 339.43 | 20.70 | 42.4 | 0.72 |
| 23.7 | 16.23 | 30.48 | 21.48 | 306.86 | 22.76 | 40.2 | 0.60 |
| 22.4 | 16.18 | 30.61 | 21.92 | 313.14 | 20.98 | 41.8 | 0.48 |
| 23.8 | 16.14 | 30.18 | 20.38 | 291.14 | 16.45 | 44.1 | 0.36 |

| Temp. (C) | Moisture (% wb) | Air hum. (%) | Radiation (mV) | Radiation (kW/m ²) | Efficiency (%) | Gate Angle (degrees) | Dryingrate (%/h) |
|--------------|--------------------|-----------------|-------------------|-----------------------------------|-------------------|-------------------------|---------------------|
| 21.6 | 16.11 | 29.76 | 22.00 | 314.29 | 13.27 | 43.2 | 0.36 |
| 27.3 | 16.08 | 28.82 | 20.50 | 292.86 | 12.29 | 43.9 | 0.12 |
| 25.6 | 16.07 | 30.06 | 8.68 | 124.00 | 4.40 | 43.9 | 0.36 |
| 26.0 | 16.04 | 34.64 | 7.90 | 112.86 | 31.16 | 32.2 | 0.48 |
| 25.5 | 16.00 | 35.16 | 28.62 | 408.86 | 45.64 | 24.6 | 0.36 |
| 26.1 | 15.97 | 35.36 | 22.21 | 317.29 | 9.45 | 43.7 | 0.36 |
| 25.5 | 15.94 | 35.16 | 28.62 | 408.86 | 12.18 | 43.7 | 0.48 |
| 26.1 | 15.90 | 35.36 | 22.21 | 317.29 | 12.60 | 43.5 | 0.36 |
| 25.5 | 15.87 | 34.96 | 24.85 | 355.00 | 12.18 | 43.5 | 0.12 |
| 25.4 | 15.86 | 34.91 | 24.98 | 356.86 | 3.63 | 43.5 | 0.12 |
| 25.9 | 15.85 | 35.01 | 25.60 | 365.71 | 3.61 | 43.5 | 0.12 |
| 25.9 | 15.84 | 35.59 | 24.80 | 354.29 | 3.52 | 43.3 | 0.24 |
| 25.5 | 15.82 | 36.40 | 20.53 | 293.29 | 7.27 | 43.1 | 0.24 |
| 25.7 | 15.80 | 36.47 | 16.80 | 240.00 | 8.78 | 43.1 | 0.12 |
| 25.6 | 15.79 | 36.42 | 16.88 | 241.14 | 5.37 | 43.0 | 0.12 |
| 25.6 | 15.78 | 36.70 | 17.96 | 256.57 | 5.34 | 0.0 | |

Average 27.1 37.04 367.17 23.50 40.1 0.64

* The value of radiation in column 4 is in milivolts mV

* The values correspond to 5 minute intervals

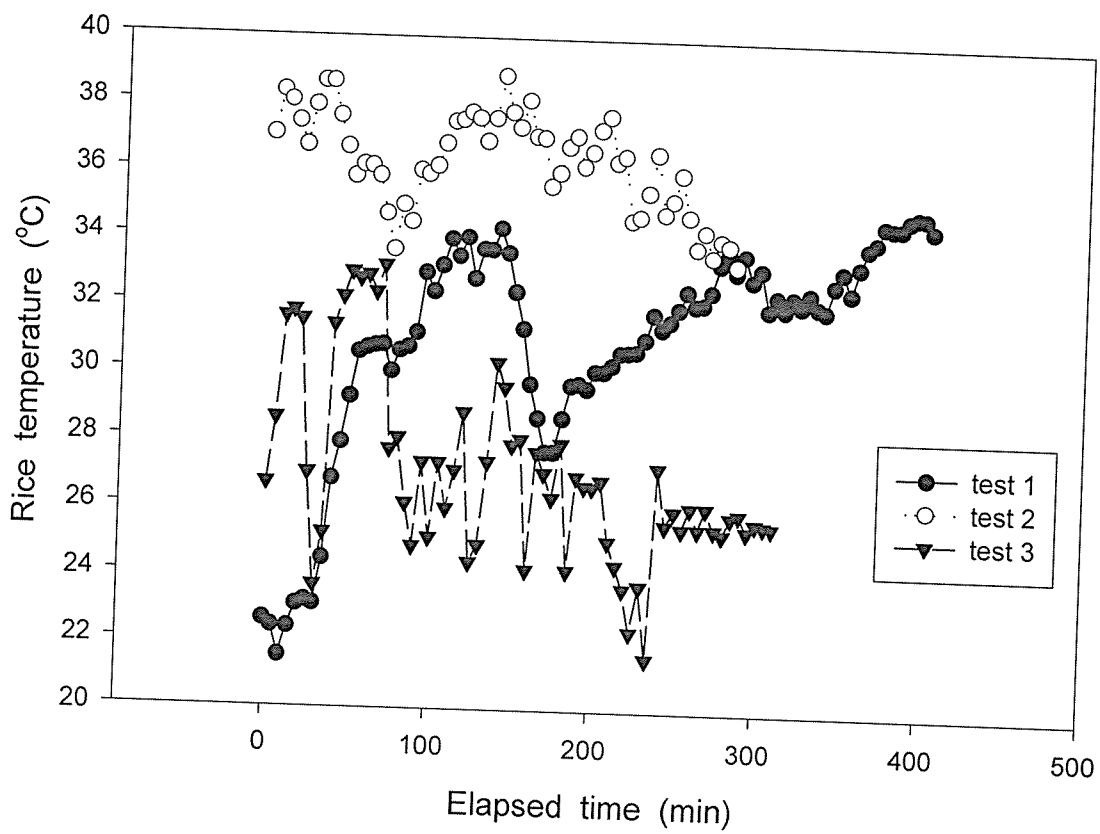


Fig. 1a Variation of rice temperature

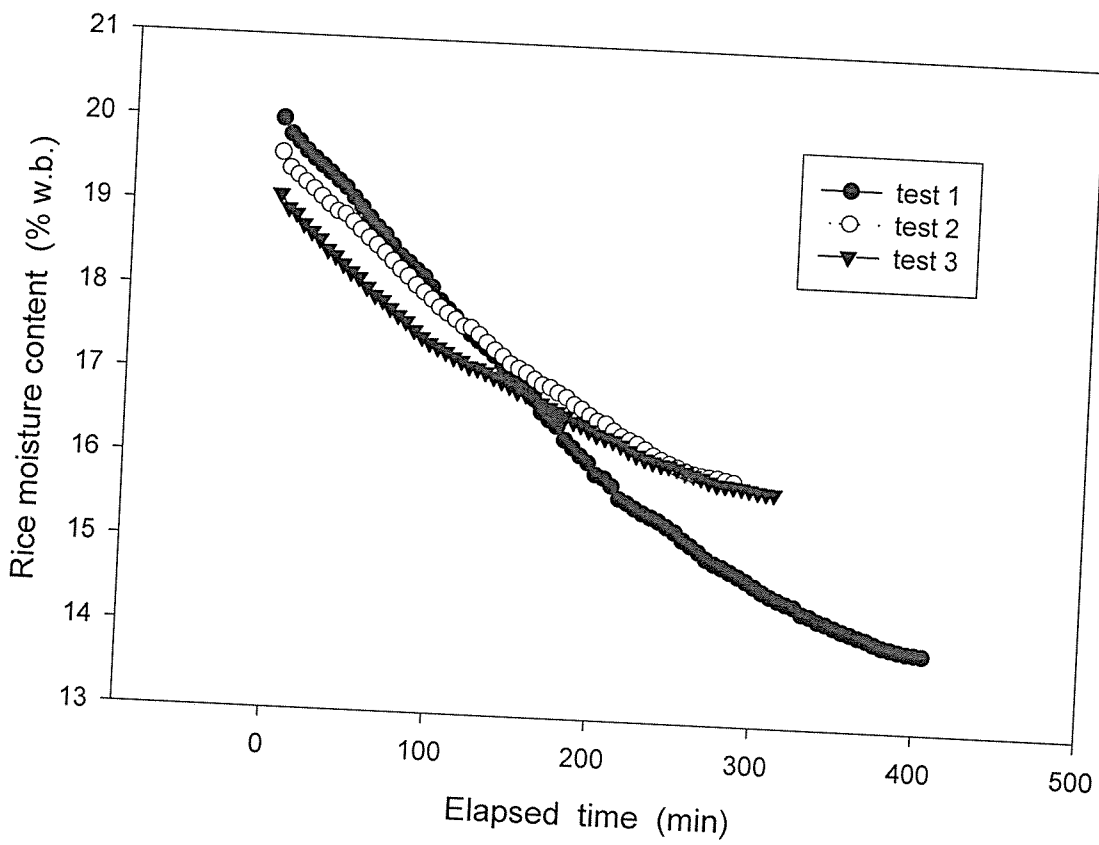


Fig. 2a Variation of rice moisture content

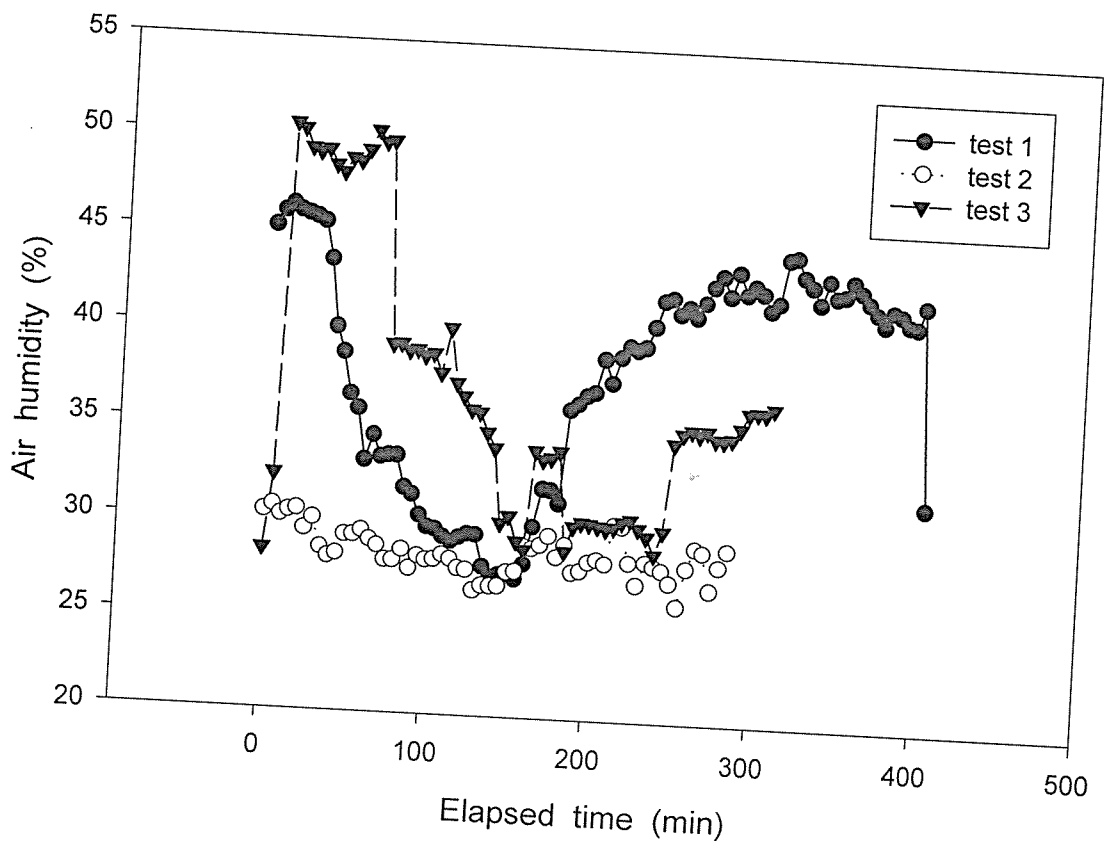


Fig. 3a Variation of air humidity

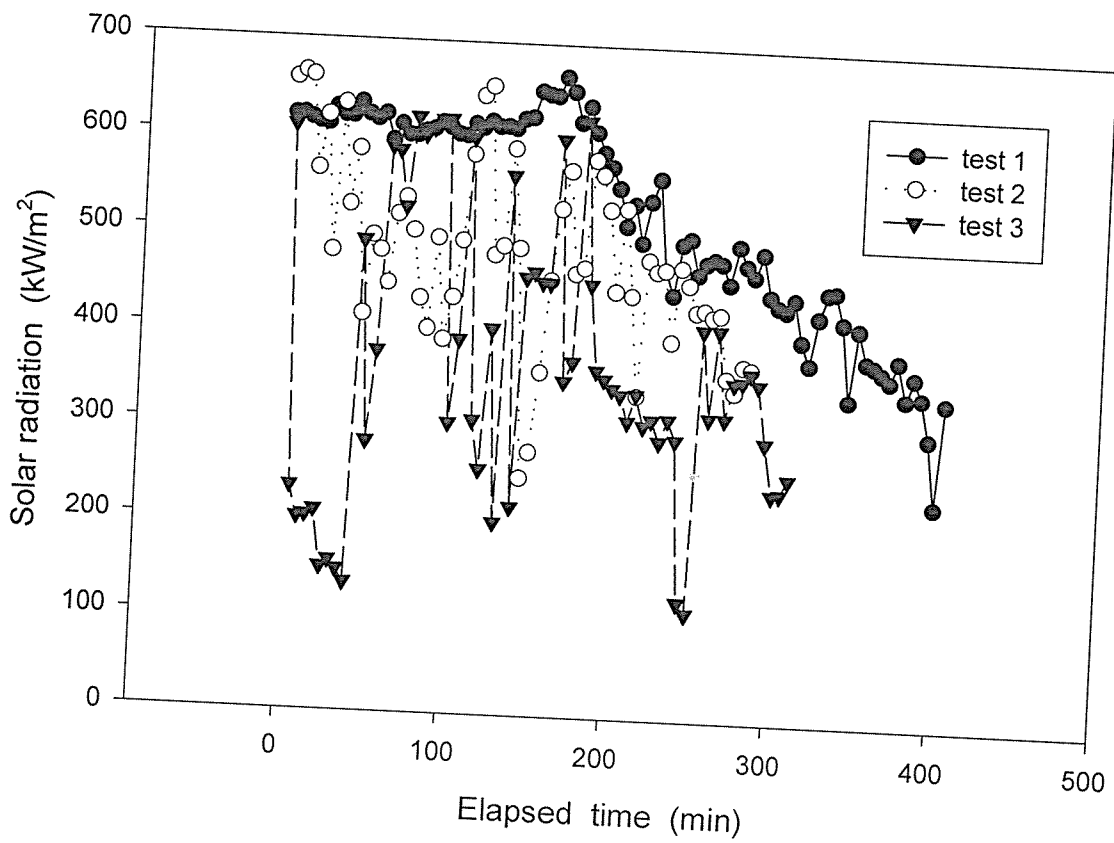


Fig 4a. Variation of solar radiation

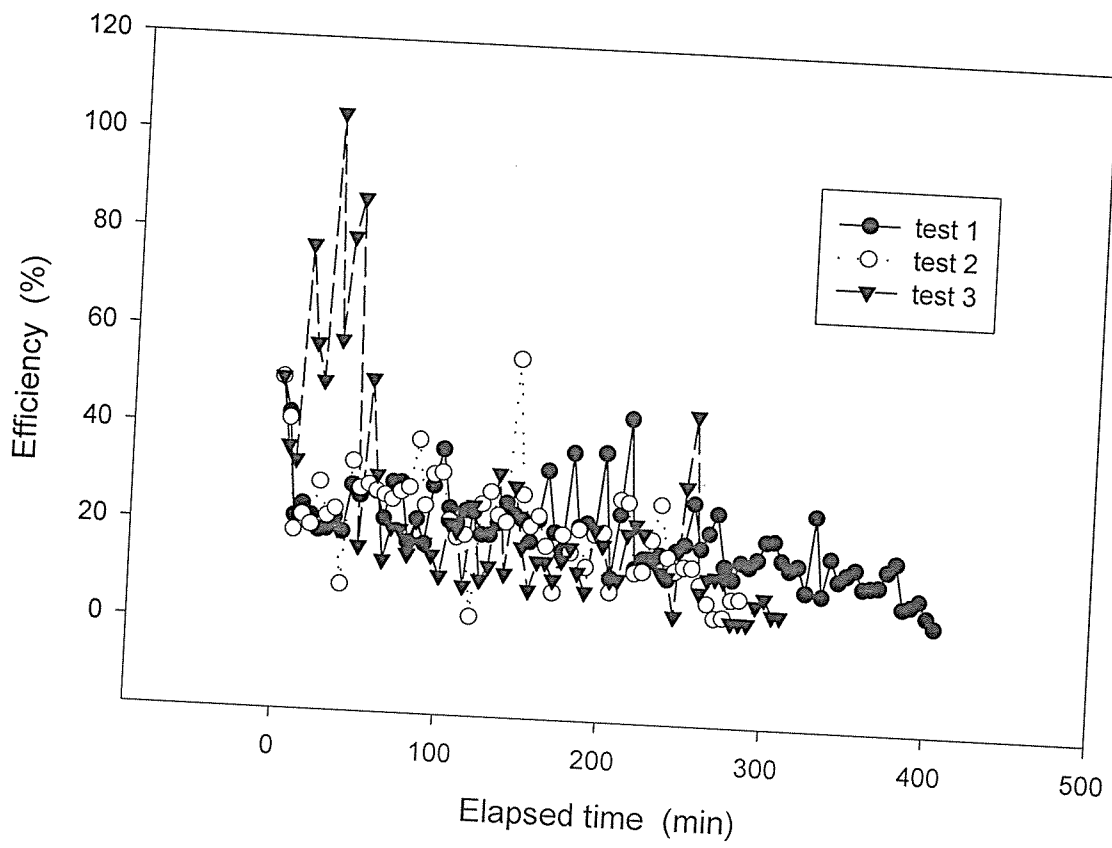


Fig. 5a Variation of efficiency

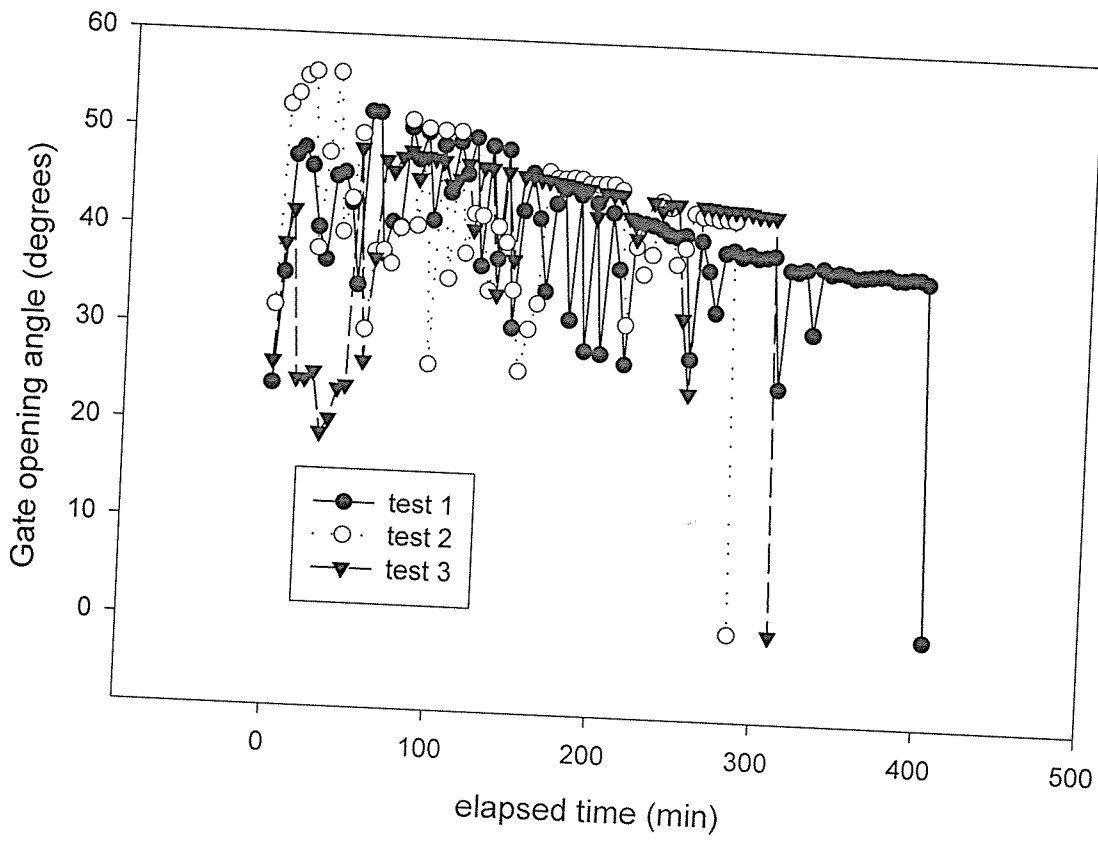


Fig. 6a Variation of the opening on the inlet gate

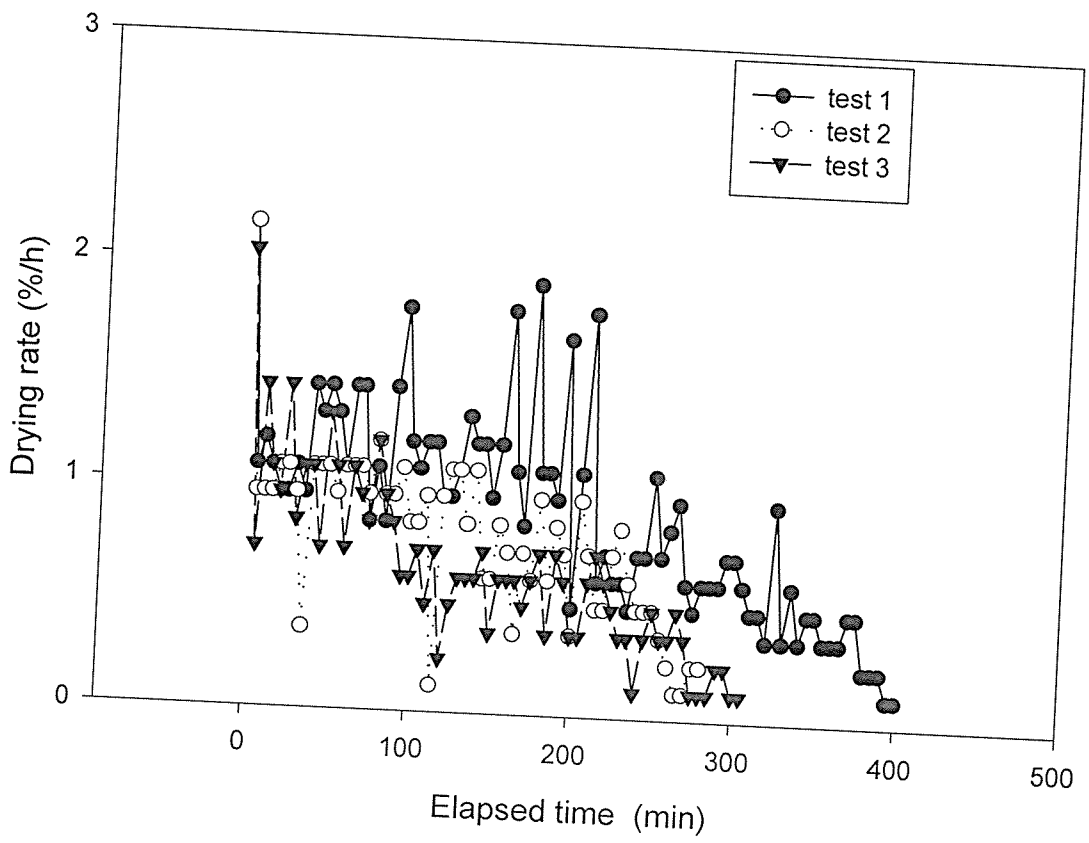


Fig. 7a Variation of drying rate