# Design and evaluation of a compact thermal storage system using river stones for a continuous process of agricultural products in Peru

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**Abstract**

Drying only during the day is a problem for the solar drying process of several products in Peru, for this reason a low-cost thermal storage system that can carry out a continuous drying process has been designed. This system consists of an insulated bed filled with storage material, 400 kg stones of the river, and a solar air heater with 2.8 $m^2$ of area to extract thermal energy from the sun for the air. The system was tested with two mass flow rate, from 0.0311 kg $s^{-1}$ and 0.0251 kg $s^{-1}$, to determine the optimal speed. The maximum temperature obtained in the stones was 50.3 ° C, 30 degrees more than the ambient temperature. In addition, the maximum energy obtained is given at 3:30 p.m. The discharge efficiency was 57.7% and the collection of 39.4% taking into account that the heat loss found was 1°C per hour. The experimental results were similar to the theoretical results with a maximum difference of 4.1° C.

*Keywords: Solar thermal energy, drying, thermal storage, rural sector, productive use.*

## 1. Introduction

Currently, in Peru, the most commonly used method that has become traditional is direct drying exposed to the sun. It is an economic method for the conservation of agricultural products for commercialization and/or consumption. However, exposure is to both sunlight and the environment; this generates non-uniform drying, since the variables such as air speed, temperature, and relative humidity are not controlled. Likewise, the product, when exposed to the environment, is affected by animals, insects, rain and debris, and generates significant losses (Kumar et al., 2016).

Although the vast majority of crop production is sun-dried, there are innovations in solar dryers, such as tunnel-type dryers, where the quality of the product is preserved, but they are not entirely efficient; drying is discontinuous because it is only done during the day and not during the night. The discontinuous drying brings consequences such as the re-humidification of the product because at night the air is colder and gains moisture. This, in addition to affecting the quality of the product, delays drying for several days.

It is proposed to continue drying during the hours when the sun does not intervene, making solar drying a continuous and efficient process. It is proposed to make use of solar thermal energy in the design of a thermal storage system using river stones and achieve an increase in temperature or maintain constant temperature during the night; improving the quality of the dry agricultural product avoiding its re-humidification at night when using a continuous process. With this form will also reduce the time of the drying process.

This thermal storage system is built with easily accessible materials such as wood, glass, stones, etc. It is also important to optimally select the size of the stones to be around 5 cm in diameter equivalent to not have too many pressure losses and store the maximum possible energy (Maithani, R. et al., 2003).

This system has been built and installed in Cieneguilla, Lima, Peru (fig 1) with coordinates 12°04'10.0"S 76°45'15.5"W.

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transformation and conservation of pickled chili in Lambayeque, using renewable energies."

## 2. Nomenclature

| Quantity | Symbol | Unit |
|---|---|---|
| Area of solar collector | $A_r$ | $m^2$ |
| Cross-sectional area of the bed with stones | $A_c$ | $m^2$ |
| Specific heat of air | $c_a$ | $J\ kg^{-1}\ K^{-1}$ |
| Specific heat of river stone | $c_s$ | $J\ kg^{-1}\ K^{-1}$ |
| Period of data taken | $dt$ | s |
| Equivalent spherical diameter | $D_e$ | m |
| Volumetric heat transfer coefficient | $h_v$ | $W\ m^{-3}\ K^{-1}$ |
| Global irradiance | $G$ | $W\ m^{-2}$ |
| Mass flow rate | $\dot{m}_a$ | $kg\ s^{-1}$ |
| Total number of river stone | $N$ | - |
| Heat energy collected in the bed with stones | $\dot{Q}_c$ | W |
| Heat energy retrieved from the bed with stones | $\dot{Q}_{rc}$ | W |
| Time | $t$ | s |
| Inlet air flow temperature | $T_{ai}$ | K |
| Outlet air flow temperature | $T_{ao}$ | K |
| Ambient temperature | $T_a$ | K |
| Total volume of the river stone | $V_t$ | $m^3$ |
| Temperature gradient of node | $dT/dt$ | $K\ s^{-1}$ |
| Thickness of the nodal elements | $\Delta x$ | m |
| Density of air | $\rho_a$ | $kg\ m^{-3}$ |
| Density of the river stone including voids | $\rho_s$ | $kg\ m^{-3}$ |
| Void ratio | $\varepsilon$ | % |
| Packed bed collector efficiency | $eta_c$ | % |
| Heat retrieval efficiency of the bed | $eta_{rc}$ | % |

## 3. Methodology used

This work is based on the study of energy efficiency of a thermal storage system consisting of a bed with stones proposed by Panna Lal Singh in 2015. To achieve a continuous process in any solar dryer, a storage system with river stones was used to store thermal energy during the day and inject it overnight into a dryer; these operations are illustrated in figure 2.

The isolated bed has a capacity of 0.3 $m^3$; it was full of river stones with diameters of 4.5 cm and the area of the solar air heater is 2.8 $m^2$.

The tests were carried out following a test protocol consisting of three phases. First, the system was tested in different airflows to obtain the temperature curve of the bed versus the speed, establish the hours at which the stone bed was reached maximum temperature, and obtain the maximum stored energy. Second, with the optimum speed, the isolation time of the bed was obtained after reaching the maximum stored energy. Finally, the heat discharge time and the efficiency of the system were determined.

**Fig. 1 Installation of the thermal storage system in Cieneguilla, Lima, Peru**

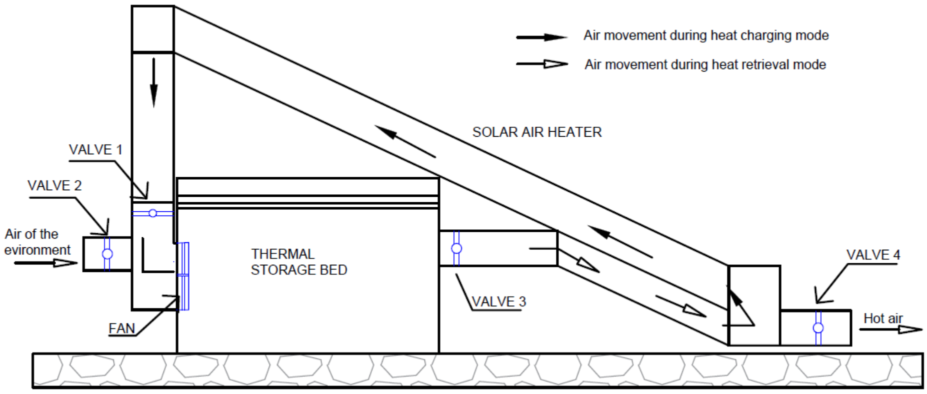


**Fig. 2 Diagram of the parts and operation of the thermal storage system**

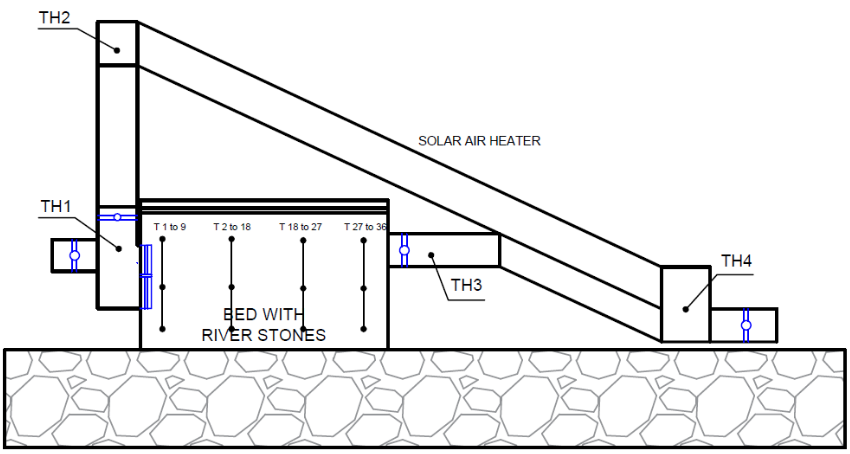


**Fig. 3. Diagram of sensors inside the thermal storage system.**

## *3.1 Measurements*

A measurement system was built with an ATMega 2560 microcontroller where data was recorded every 1 minute. Temperature of the bed, temperature before the bed, temperature after the bed, temperature before the solar air heater, temperature after the solar air heater, the ambient temperature, and the global irradiance were recorded. The temperature in the bed was measured in 36 points located uniformly throughout its volume (figure 3) in order to compare the results with the simulation of the bed.

**Tab. 1: Physical properties of the rock pebble packed bed.**

| Parameters | Values |
|---|---|
| Specific heat of the river stone | 0.8 kJ $kg^{-1}$ $K^{-1}$ (Kürklü, 2003) |
| Porosity of river stones | 42% (measured) |
| Density of river stones include voids | 1350 kg $m^{-3}$ (measured) |
| Equivalent diameter of rock pebbles | 45 mm [ calculated from eq. (1)] |
| Specific heat of air | 1000.5 kJ $kg^{-1}$ $K^{-1}$ (Kürklü, 2003) |
| Density of air | 1.1 kg $m^{-3}$ (Singh, 2015) |
| Volumetric heat transfer coefficient of bed with stones | 1363 W $m^{-3}$ $K^{-1}$ [ calculated from eq. (6)] |

## 3.2 Determination of equivalent rock pebble diameter, porosity, and pebble density

The porosity was determined by measuring the volume of a container with rock pebbles and the volume of water in the same container. Division of the former to the latter one gave the porosity of rock pebble bed (Kürklü et al., 2003). Equivalent diameter (*De*) of the rock pebbles was calculated by using the equation given below (Chandra et al., 1981):

$$D_e = [\frac{6V_p(1-\epsilon)}{\pi N_p}]^{1/3} \quad \text{(eq. 1)}$$

Density of the rock pebbles was determined by net weight of the pebbles in the container divided by volume of the container. Taking the container volume into consideration, the density was then expressed as kg $m^{-3}$ (Singh., 2015). The thermo-physical properties of the used rock pebbles bed are given in Table 1.

## 3.3 Solar energy collection and heat retrieval efficiencies

Following equations were used in the calculations of solar energy collected and energy recovered respectively;

$$Q_c = m_a c_a (T_{ai} - T_{ao}) \quad \text{(eq. 2)}$$
$$Q_{rc} = m_a c_a (T_{ao} - T_{ai}) \quad \text{(eq. 3)}$$

Daily solar energy collection and energy recovery efficiencies were determined respectively, as follows;

$$eta_c = \frac{\int_{t1}^{t2} Q_c dt}{\int_{t1}^{t2} G A_c dt} \quad \text{(eq. 4)}$$

$$eta_{rc} = \frac{\int_{t1}^{t2} Q_{rc} dt}{\int_{t1}^{t2} Q_c dt} \quad \text{(eq. 5)}$$

## 3.4 Modelling of the bed with river stones

The energy equations that govern the heat transfer in the thermal storage system are based on the following assumptions. The stone accumulator is uniformly packed and has the same bulk density and uniform apparent thermal capacity throughout. The thermal gradient within the solid particles is negligible. The transfer of heat in the rocks in the radial direction was neglected. The numerical approximation of the infinite difference was applied to model the bed of river stones. The bed of river rocks was divided into segments/nodes of equal thickness in the opposite direction to the air flow. The temperature of the fluid (air) in the center of each segment was calculated using the developed model. The volumetric heat transfer coefficient (*hv*) was calculated as given below (Löf and Hawley, 1948):

$$h_v = 652[\frac{m_a}{A_r D_e}]^{0.7} \quad \text{(eq. 6)}$$

If the calculated value of the *hv* is quite high, it can be said that the air temperature and the temperatures of the stones are considered equal at any node. The following rule was used for the stability of numerical equations (Garzoli, 1989):

$$\frac{h_v A_r \Delta x}{m_a c_a} < 1 \quad \text{(eq. 7)}$$

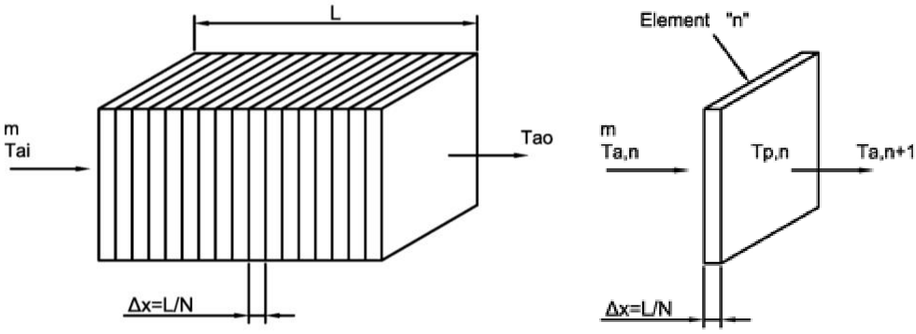


**Fig. 4 Diagram of the mathematical model of the bed with river stones**

The entire bed was divided into 30 nodes/segments and the thickness of each segment was 0.041 m, an example of the illustrated model is shown in figure 4. The energy balance of any node was as indicated below:

$$\rho_s c_s A_r \Delta x \left(\frac{dT_{p,n}}{dt}\right) = m_a c_a (T_{a,n-1} - T_{a,n}) \quad \text{(eq. 8)}$$

Considering that the temperatures of the air and the stones are equal, $T_{a,n} = T_{p,n}$ the above equation can be rewritten as:

$$\rho_s c_s A_r \Delta x \left(\frac{dT_{p,\mathrm{n}}}{dt}\right) = m_a c_a (T_{a,n-1} - T_{p,n}) \quad \text{(eq. 9)}$$

Considering any step 'P' and the next step 'P + 1', the above equation can be expressed as:

$$\rho_s c_s A_r \Delta x \left(T_{p,n}^{P+1} - T_{p,n}^{P}\right) = h_v A_r \Delta x (T_{a,n-1}^{P+1} - T_{p,n}^{P+1}) dt \quad \text{(eq. 10)}$$

By maintaining the period interval (dt) for the data in one minute (60 s, expecting a slow increase / decrease in the temperature of the bed), the value of $T_{p,n+1}^{P}$ can be obtained from the above equation written as:

$$T_{p,n}^{P+1} = \frac{(60\text{ s}) m_a c_a T_{a,n-1}^{P+1} + \rho_s c_s A_r \Delta x T_{p,n}^{P}}{(60\text{ s}) m_a c_s + \rho_s c_s A_r \Delta x} \quad \text{(eq. 11)}$$

To calculate in the next step, $T_{p,n}^{P}$ was taken equal to $T_{p,n+1}^{P}$ and the calculations continued until the required final time.

## 4. Results and discussion

### *4.1 Average temperature of the river stones vs time with different mass flow rate*

This part of the experiment was done in order to find the maximum energy stored in the river stones, which depends on the maximum average temperature reached, and the time of day it is reached. In this stage, the thermal storage system was evaluated at different mass flow rate, which were 0.0311 kg $s^{-1}$ as shown in fig. 5 and 0.0251 kg $s^{-1}$ as shown in fig. 6. The prototype was operating in a closed cycle, which implies that valves 1 and 3 are open, and valves 2 and 4 are closed.

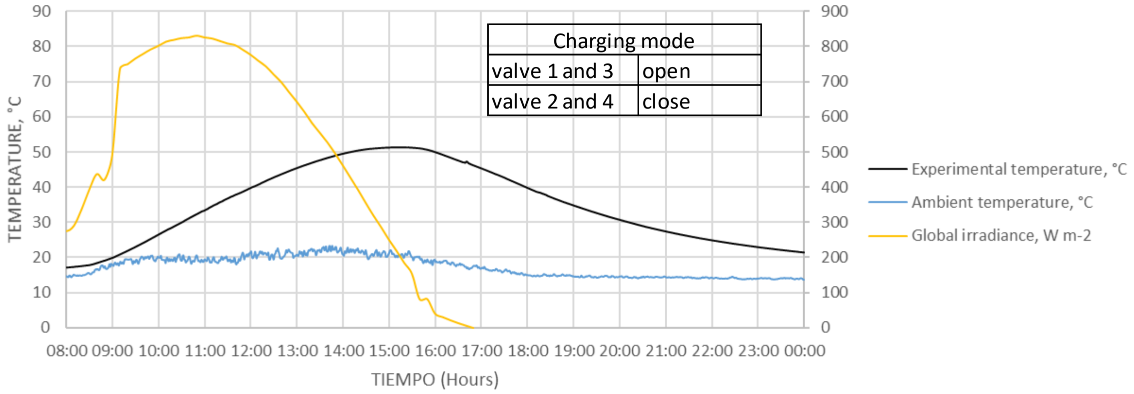


**Fig.5: Behavior of the bed temperature, solar radiation and ambient temperature. Mass flow rate = 0.0311 kg $s^{-1}$**

In fig. 5 the maximum average temperature in the stones is 50.5 °C with a difference of 30.5 °C with respect to the ambient temperature (20 °C). In fig. 6, the maximum average temperature in the stones is 45.5 °C with a difference of 25.5 °C compared to the ambient temperature (20 °C).

In fig. 5 and 6, the maximum temperature obtained in the stones is reached around 3:30 PM.

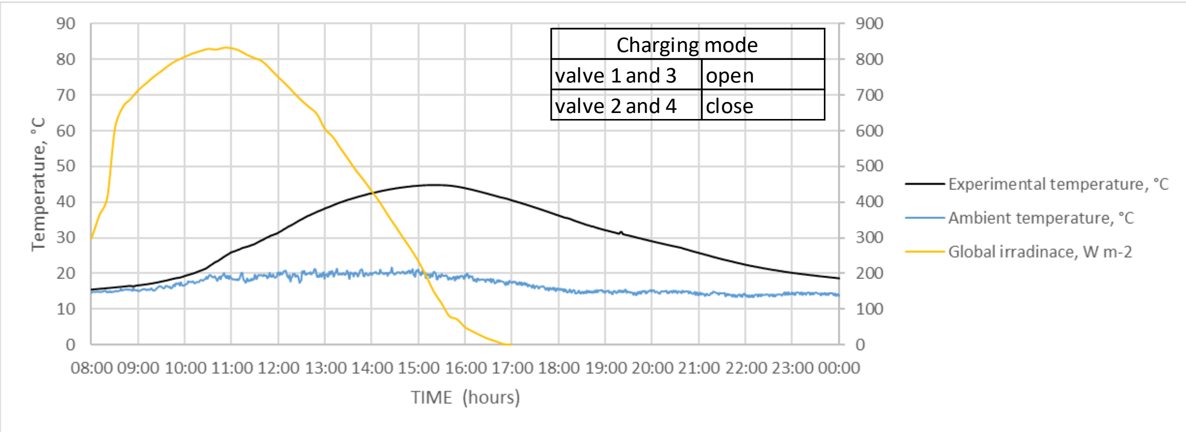


**Fig.6: Behavior of the bed temperature, solar radiation and ambient temperature. Mass flow rate = 0.0251 kg $s^{-1}$**

### *4.2 Rate of heat loss through insulation of the bed with river stones after reaching the maximum temperature*

In this part of the experiment, the objective was to find the time in which the river stones lost the heat gained by the air circulation system. In this stage, the thermal storage system with the mass flow rate of 0.0311 kg $s^{-1}$ was evaluated as shown in fig. 7 because at that mass flow rate the maximum average temperature of the river stones was obtained. The prototype was operating in a closed cycle, which implies that valves 1 and 3 are open, and valves 2 and 4 are close until 3:30 pm, then all valves closed and the fan turned off.

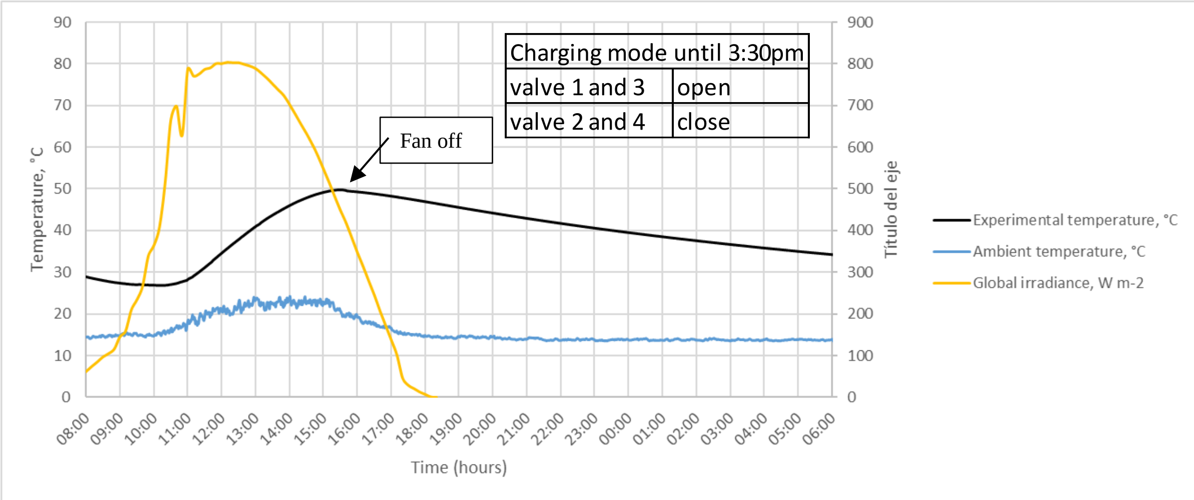


**Fig.7: Behavior of the bed temperature, solar radiation and ambient temperature. Mass flow rate of charge = 0.0311 kg $s^{-1}$and fan off at 3:30 pm.**

In fig. 7, the maximum temperature reached was 50 °C with a difference of 30 °C with the ambient temperature (20 °C). In addition, the loss of temperature is very similar to a linear function and is lost at a rate of 1 °C per hour.

### *4.3 Efficiency of the energy returned from the bed with river stones and retrieval time*

The objective of this stage was to find the time in which the system was discharged and its efficiency. In addition, the theoretical and experimental components of the average stone temperature were compared.

The prototype operated in load mode (valve 1 and 3 are open and valves 2 and 4 are closed) and with a constant mass flow rate of 0.0311 kg $s^{-1}$ until 3:30 pm as shown in fig. 8. Immediately after, it operated in discharge mode (valves 1 closed and valves 2, 3 and 4 open) with a mass flow rate of less than 0.0161 kg $s^{-1}$ in order to increase the discharge time. In the discharge mode, the air that enters the bed with river stones is at room temperature.

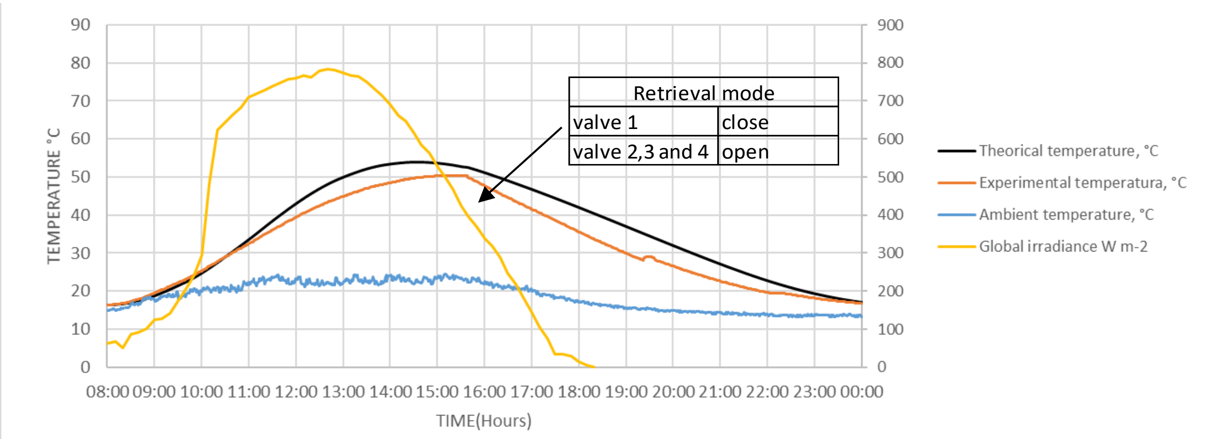


**Fig.8: Behavior of the bed temperature, solar radiation and ambient temperature. Mass flow rate of charge = 0.0311 kg $s^{-1}$, discharge = 0.0161 kg $s^{-1}$ (at 3:30 pm).**

For the realization of the test, 2 days after the initial one, the similarity of radiation levels with the previous test was assured. In fig. 8, the maximum temperature reached is 50 °C at 3:30 pm with a difference of 30 °C with respect to the ambient temperature (20 °C). The energy gained by the system was 12.63 MJ and the energy returned was 7.29 MJ with an efficiency of 57.7%. Efficiency is low due to heat losses through insulation. In addition, the theoretical and experimental curves are very close with a difference of 4.1 °C.

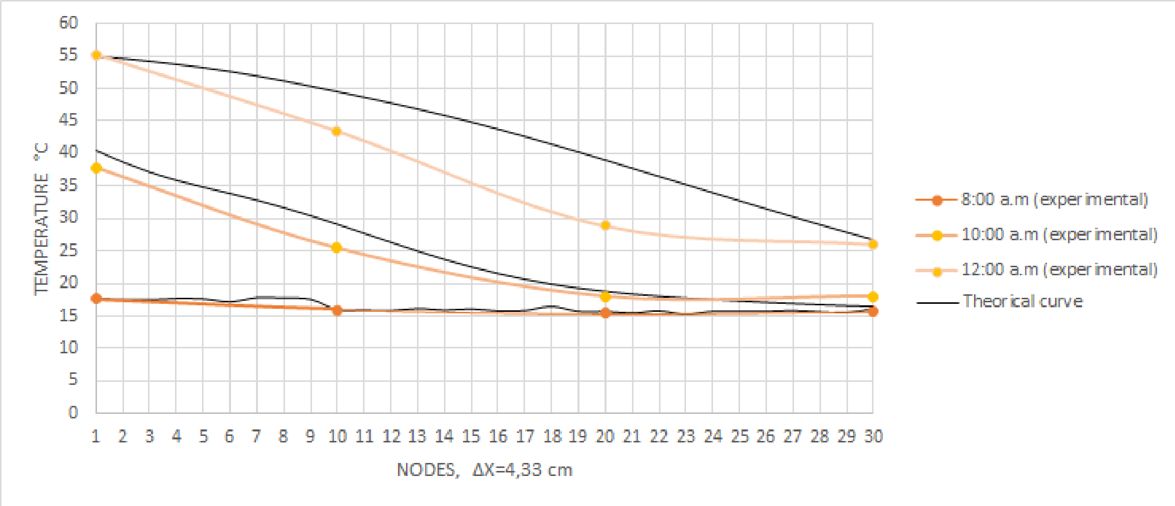


**Fig.9 Behavior of the temperature throws the bed during the charge.**

In fig, 9 the temperature varies throughout the bed with river stones at the time when the system is charging. In addition, the comparison between the theoretical and experimental curve model. The river stones are heated at the entrance of the hot air, which comes out colder at the exit.

## 5. Conclusions

Temperature of the river stones was raised up to 50.3 °C from 16 °C during charging mode.

The temperature values obtained from the mathematical model compared with the experimental data were acceptable.

In addition, using the thermal storage system in charging mode until 3:30 pm allows a discharge efficiency of 57.7% and the collection efficiency of 39.4%

This system uses materials that are easy to find in rural areas, which makes it economical. On the other hand, hot air can be used in other applications, such as heating schools and homes in very cold rural areas.

## 6. References

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