Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

# DIRECT ILLUMINATED ROCK-BED HEAT STORAGE A POTENTIAL COMPONENT OF A SOLAR THERMAL SYSTEM FOR FOOD PRESERVATION AND SPACE HEATING IN RURAL AREAS OF MOZAMBIQUE

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## Abstract

Sun drying is a well known method of food preservation in countries with high level of solar irradiation and one of the ancient applications of solar energy. This method is widely applied for drying different agricultural products, meat and fish in rural areas of Mozambique. However, sun drying is ineffective method for food preservation and lead to poor product quality and post harvest losses. A more effective method of solar radiation deployment for food preservation is solar drying, which involves solar dryers. But many of them are direct solar dryers. Therefore they exhibit the same intermittent nature as the source of radiation does, which turn them useless devices during off-sun conditions. In order to extend the usefulness of solar dryers even in off-sun conditions, heat storage must be incorporated. In this study, in an in-door test, the potential of a direct illuminated rock-bed heat storage based on natural convection of air is experimentally investigated. The results show a good potential of rock-bed heat storage to supply thermal energy for low-to-medium temperature applications.

Keywords: *Direct illumination, heat storage, solar drying, space heating, sun drying, natural convection and food preservation*.

## 1. Introduction

Mozambique is a Southern African country and share common characteristics with the other African countries in that the majority of its population lives dispersed in rural areas, far from the national electricity grid. In fact only 18 % of Mozambican population is connected to national electricity grid (IRENA, 2012). The major fraction of population has biomass as major source of energy for different domestic needs. According to IRENA (2012), biomass contributes with more than 78 % of primary energy.

A source of growing concern, however, is the fact that one of the major sources of biomass is increasingly becoming scarcer due to unsustainable use of forest resources, land use change and also desertification (Cuamba et al, 2006; Chikukwa, 2008). While the burning of biomass has become a common practice among the emerging small commercial farmers in Mozambique for drying tobacco, the gains from this agricultural crop may be reduced if this trend remains as it is.

Fortunately, the country is among those possessing high levels of solar radiation (Nijegorodov et al, 2003; Cuamba et al; 2006). Therefore, solar thermal energy may be useful for drying different agricultural products including tobacco and other foodstuff either used as a solely source or used in a complementary way with the other sustainable sources of thermal energy.

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doi:10.18086/swc.2015.02.13 Available at http://proceedings.ises.org

of ancient applications of solar energy. However, sun drying as it is done under environmental conditions is ineffective method of food preservation due to constraints it presents and lead to poor product quality and spoilage leading thereby to postharvest losses, as discussed in Weiss & Buchinger (2012) and also by Raman et al. (2012).

Some of the pitfalls imposed by sun drying can be removed by the adoption of solar drying techniques. Solar drying involves the use of solar dryers and leads to more heat supply to the products than that available in natural conditions thereby turning the use of solar radiation into a more effective process (Weiss & Buchinger, 2012; Bala & Debnath, 2012: Raman et al. 2012).

Solar dryers can be natural convection and forced convection based. But many solar dryers enable the drying activity while solar radiation is present and are not useful during off-sun conditions. For this to happen, heat storage must be integrated.

The integration of heat storage enables the collection of solar thermal energy during day light and its storage for later use. The stored thermal energy can be used either to supply heat to the dryer or to be used for the space comfort in winter in absence of solar radiation, enabling this way overnight drying process of the products and space heating.

There are different ways to charge the storage. In one of the ways, the absorbing material and the storage are separate units; in this case a carrier medium is needed to transport heat from the absorber and charge the storage. In the other, in which the need of a carrier medium is bypassed, the absorber is an integrated part of the storage, in which case the storage is directly illuminated.

Although, in general, forced convection solar drying is an advantageous process as compared to natural convection solar drying, the requirements of forced convection solar dryers are not affordable to many rural families in Mozambique due to additional costs the forced convection generator brings. In fact, the cost associated with the forced convection generator is pointed as a constraint to implementation of forced convection solar dryers in low income families (Bala & Debnath, 2012).

Thus, despite the limitations of indirect natural convection solar dryers when applied to commercial and industrial scales as argued by (Bala & Debnath, 2012), some of them may be suitable to domestic applications for drying agricultural products and space heating. Thus, in this study, the potential of a side illuminated Rock-bed heat storage with natural convection as heat transfer mechanism to enable off-sun indirect solar drying of food and space heating is experimentally investigated.

## 2. Background Information

Solar drying of agricultural crops and different foodstuff is recognized as a midterm between the expensive and environmental damaging process of burning wood and fossil fuels and the traditional and vulnerable process of sun drying (Raman et al, 2012). In its extensive and comprehensive review Raman et al (2012) provides the state of art in solar drying technologies in developing countries, giving more emphasis to technologies enabling off-sun drying, and recognizes the benefits arising from its adoption from financial and environmental point of view.

Off-sun drying requires integration of heat storage. Then solar thermal energy must be collected during day light and carried to the storage; from which it can be extracted when needed. At some point in this paper two modes of charging the storage were mentioned: one that requires a heat carrier medium from the collector to the storage, and the other where the need of a heat carrier medium is bypassed. In the later, the storage is directly illuminated and heat is absorbed by the storage material.

During heat extraction, a fluid must be heated in interaction with the storage material. Then, the fluid carries the heat to the dryer. Again, the process can be carried out through two different modes of heat transfer namely natural convection which depends entirely on buoyancy force, and forced convection which require the forced convection generator.

Some studies devoted their attention in reviewing different types of dryers and discussing their performances and applicability in developing countries. In addition, they presented the current status of solar dryers and discussed the potentials of solar drying technology by revisiting their experimental performance in tropic and sub tropic regions as well as simulation of some of the types of dryers (Weiss & Buchinger, 2012) and others

designed, developed and tested a forced/ Natural convection solar vegetable dryer with heat storage (Babagana et al., 2012).
It is widely recognized that forced convection is an advantageous process over natural convection. In fact, (Babagana et al. 2012) found that forced convection mode was more efficient in that it enabled higher air flow and control in addition to reduced drying time. Due to additional costs that the forced convection generator brings, it may be suitable for commercial and industrial dryers, but not adequate for low income rural families, in which case the natural convection based solar dryers may be useful as a tool for drying agricultural products and other kinds of food at small scale applications and also for space heating applications. In fact in Raman et al. (2012) review, one of the focuses was on indirect natural convection based solar dryers with heat storage. Several studies referred in this review paper related to this type of dryers recognize the suitability and benefits of indirect natural convection based solar dryers to be applied in small farms in rural areas of developing countries. Bergman et al. (2011) also recognize that whenever and wherever heat transfer and operating costs have to be minimized, then natural convection based systems is the recommended choice.

Natural convection dryers are more popular for drying agricultural products owing to their low cost, simplicity in operation and maintenance; but presents lower drying rates, hence longer drying time than their counterpart (Babagana et al., 2012; Bala & Debnath, 2012). However, solar dryers regardless of their category are more effective than sun drying, because they lead to reduced drying time and good quality product.
In their turn Othman et al. (2006) devoted their attention to solar dryers with heat storage, that also integrate auxiliary sources of energy and controlling structure to allow off-sun drying activity of agricultural products.

With the similar purpose and recognition of the need to supplant the pitfalls brought about by the intermittent nature of the solar radiation, five years later after Othman's paper, Bal et al.(2011) published a review paper that focused to solar dryers with PCM heat storage.

### *2.1. The Physics of Natural Convection*

The extent to which natural convection of a fluid occurs is dependent on buoyancy force. The driving force of this agent is density gradient which in turn is caused by temperature gradient within the fluid (Bergman et al. 2011). In most of the cases, the ultimate driving force of a natural convection of a fluid is the interaction between temperature gradient and gravitational field.

The arising motion of the fluid must be determined by considering heat and mass transfers coupled with the fluid flow mechanisms.

The density of the fluid is a function of its temperature and their dependence at constant pressure can be expressed through the volumetric expansion coefficient $\beta$:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \qquad \text{(eq.1)}$$

For the finite variation of temperature at constant pressure, the following approximation can be used:

$$\beta \approx -\frac{1}{\rho}\left(\frac{\Delta \rho}{\Delta T}\right) \Rightarrow \Delta\rho \approx -\beta.\rho.\Delta T \qquad \text{(eq.2)}$$

Buoyancy force is proportional to density difference.

Whenever there is a relative motion between two bodies in contact, a friction forces arise at their interface; opposing to the motion.

Under steady state conditions, air flow rates driven by buoyancy are established by balancing buoyancy and frictional forces. Then, the ratio of the buoyancy force to the viscous force acting on the fluid, define the Grashof number:

$$Gr = \frac{g.\Delta\rho.V}{\rho.\nu^2} = \frac{g.\beta.\Delta T.V}{\nu^2} = \frac{g.\beta.(T_s - T_\infty).\delta^3}{\nu^2} \qquad \text{(eq.3)}$$

Natural convection over a surface, besides depending on its temperature variation and thermophysical properties of the fluid, is also geometry and surface orientation dependent.

Simple analytical relations are difficult to obtain in natural convection regimes due to the complex nature of the fluid flow. Therefore, most of the relations used to describe natural convection are experiment based correlations:

In our case, during the illumination of the storage, heated air at the entrance of the cavity rise carrying with it thermal energy; and as it goes through the voids of storage material it releases the heat to the rocks. Thus, we assume non-local equilibrium case. Then, the source of heat is interrupted.

Now we have the rocks, at the cavity entrance, at higher temperature. Therefore, the air at the vicinity of the cavity interacts with hot rocks from which it absorbs heat. Again as it goes through the voids, thermal interaction occurs and emerges at the top at temperature suitable for drying food products or space heating.

The pressure drop within the packed bed can be given by Carman-Kozeny equation:

$$\frac{\Delta p}{\Delta z} = -\frac{180.\mu.v_o.(1-\varepsilon)^2}{d_s{}^2.\varepsilon^3} \qquad \text{(eq.4)}$$

Where $\mu$ is fluid viscosity, $v_o$ is the superficial velocity, $\varepsilon$ is the bed void fraction and $\Delta z$, the bed height.

The pebble rock particles are assumed as of spherical form having a diameter $d_s$. Thus, characteristic length δ will be given by:

$$\delta = \frac{\pi.d_s}{2} \qquad \text{(eq.5)}$$

Then, heat transfer coefficient between rock pebbles and air is a function of Nusselt number, thermal conductivity of rocks and characteristic length: $h = \frac{k.N_u}{\delta}$ (eq.6)

In this equation Nusselt number expression for external convection between air and spherical rock surface is adopted. Thus,

$$N_u = 2 + \frac{0.589.Ra^{\frac{1}{4}}}{\left[1+\left(\frac{0.469}{\Pr}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \qquad \text{(eq.7)}$$

Where $Ra$ is the Rayleigh Number and $\Pr$, the Prandlt number.

The Rayleigh number is defined as the product of the Grashof and Prandtl numbers:

$$Ra = Gr.\Pr = \frac{g.\beta.(T_s - T\infty).\delta^3}{\nu^2}.\Pr \qquad \text{(eq.8)}$$

The Nusselt Number in natural convection is also given by:

$$Nu = \frac{h.\delta}{k} = C.Ra^n \qquad \text{(eq.9)}$$

Where $n$ and $C$ are constants that depend on the geometry of the surface and the flow regime.

## 3. Material and Methods

In this study a 400 mm diameter and 1000 mm height stainless steel cylinder, was adopted as a container for the storage material. Then, a cavity with same dimensions as the concentrator opening was made at its bottom side and a steel grid was welded at the cavity to hold the storage material.

The storage material comprises 257.5 kg of pebble rocks with 28 mm equivalent diameter. Afterwards two layers, of 50 mm thick, rock wool were used as thermal insulation for the heat storage.

The test was done using a solar simulator comprising a set of 7 halogen lamps and a concentrator to focus the light flux on the cavity located at the bottom side of the storage.

Experiments were performed in two different situations: At first with unglazed cavity and then with glazed cavity using borosilicate glass. In each experiment, lamps were left on for almost 4 hours and then turned off.

To monitor temperatures at different levels along the storage and also to monitor heat front progression, three thermocouples were used. Then, the sensors were connected to a dataloger interfaced to a PC through labview program to read temperatures each second.
A thermografic camera was also used to scan temperatures at the cavity.

Table 1. *Thermophysical properties of pebble rocks*

| Property | Density, $\rho\left[\frac{kg}{m^3}\right]$ | Specific Heat, $c_P\left[\frac{J}{kg.K}\right]$ | Thermal Conductivity, $k\left[\frac{W}{m.K}\right]$ | Volumetric Heat capacity, $\rho.c_P\left[\frac{MJ}{m^3K}\right]$ | Void Fraction | Average diameter, m |
|---|---|---|---|---|---|---|
| Magnitude | 2630 | 830 | 2.79 | 2.183 | 0.38 | 0.028 |

The schematic representation of the storage and the measuring points is given in the figure below.

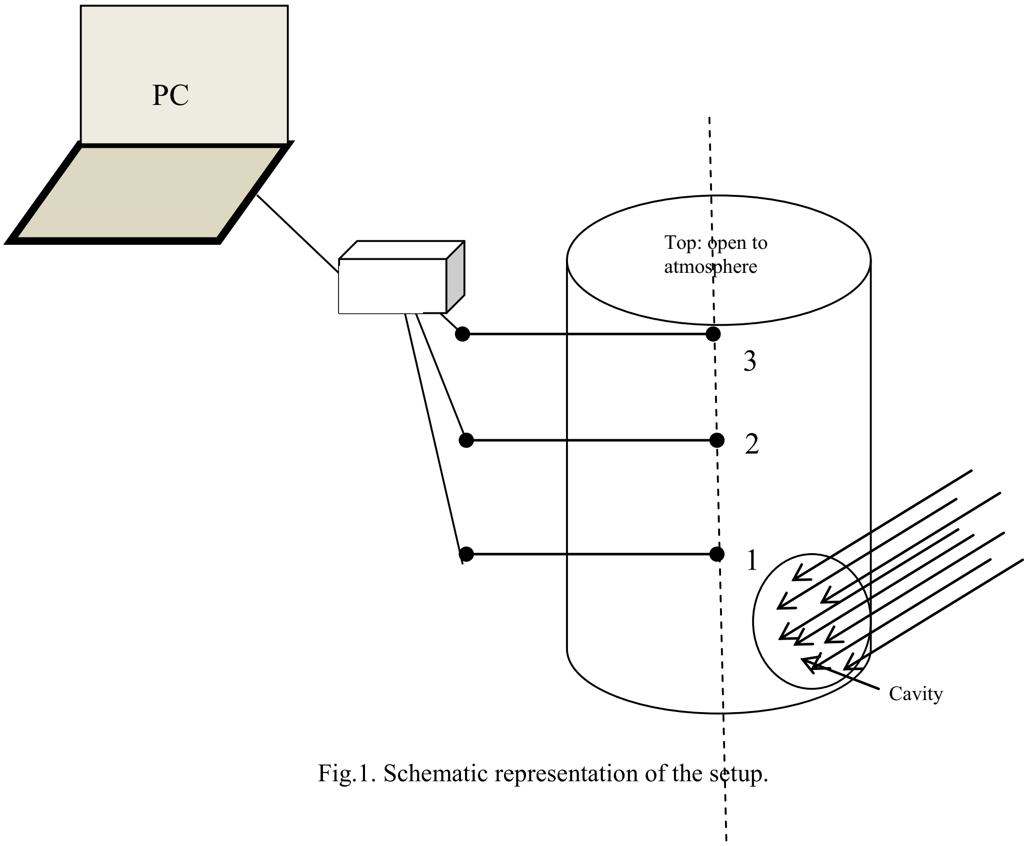

Fig.1. Schematic representation of the setup.

## 4. Results and Discussion

The following charts in figs.2 and 3 show temperature profiles at different levels of the HS for the unglazed and glazed cavity setup, respectively.

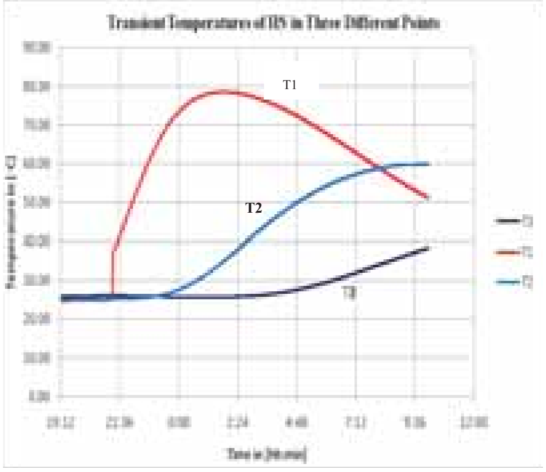

Fig.2. Chart showing temperature profiles at three different levels of HS for the unglazed cavity setup.

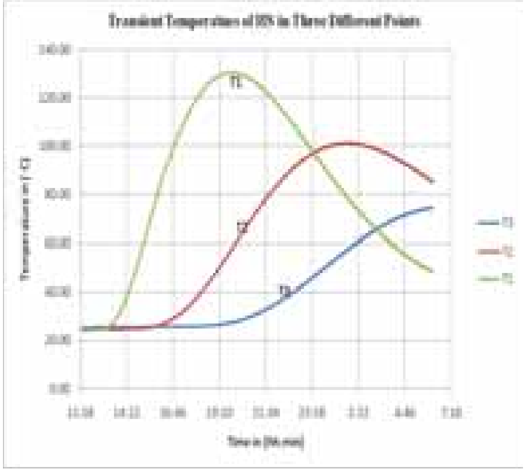

Fig.3. Chart showing temperature profiles at three different levels of HS for the glazed cavity setup.

The experiment that is referred in fig.2, was done with unglazed cavity. As can be seen from fig.2 the highest temperature registered by the first thermocouple, located 20 cm above the cavity, at the end of charging process was about 80 $^{o}$C. Readings from the sensor located at the top of the HS show that until the time reading process was interrupted, temperature went from 25$^{o}$C to around 40$^{o}$C in about 13.5 hrs and was still in rise. This represents 15$^{o}$C above initial temperature and almost 20$^{o}$C above ambient temperature.

The experiment related to the chart in fig.3 was done with the cavity covered with borosilicate glass. In order to allow the air to go through the cavity a slit of about 5 cm was left at the bottom side of the cover. From the chart in fig.3 it can be seen that the first thermocouple went until 130 $^{o}$C by the end of the charging process. The topmost sensor went until 75 $^{o}$C by the end of measurement process. This represents almost 55$^{o}$C above ambient temperature. After about 13.5 hrs temperature at the top was above 60$^{o}$C.

The fact that temperature rise at the top of the storage is observed long after the charging process is particularly important in this case because the purpose of integrating the heat storage would be fulfilled. That is, it will allow the collection of thermal energy during sunlight and its storage to enable drying of the products or space heating in the absence of sunlight (overnight or cloudy day food drying/space heating). In either case the top of the storage needs to be connected to a drying chamber or to a house through appropriate channel to allow the hot air to go through.

It is reasonable to affirm that in both cases (with or without borosilicate glass cover at the cavity) the levels of temperatures registered is consistent with drying temperatures of many agricultural products and also suitable for space heating in the regions of Mozambique presenting cold winter. However, the performance of the heat storage needs to be tested through its integration with solar thermal collection system and a drying chamber or a house in order to assure the temperature of the air delivered to the final application its indeed appropriate for the purpose.

By integrating solar thermal energy collection, thermal storage and a drying system/or a house it is possible to achieve a fairly natural convection based efficient system. Then, the updraft driving pressure difference in the system may be given by:

$$\Delta p = \rho.\frac{\Delta T}{T}.g.\Delta z \qquad \text{(eq.10)}$$

$\Delta z$ is the height difference between the air input and air exit levels (bed height)

This pressure difference will be balanced against flow friction to determine the air flow through the system.

By locating the drying and transport volumes above the solar collection and storage systems it is possible to increase the draft through the system owing to the fact that friction per unit height difference is normally smaller for the drying and transport regions than for the solar collection. In fact, Phueakphun & Fuenkajorn (2010) used a similar setup for space heating and their reasoning may be adapted in the present context to describe system‘s behavior and performance.

In our case, the storage is directly illuminated through a cavity at its bottom side by a concentrated radiation thereby being charged with thermal energy. In an outdoor experiment, a Scheffler reflector can be used to direct solar radiation to the storage’s cavity. In its turn, the storage may be connected to the drying chamber or a house, accordingly.

It should be noted that the glazed cavity setup leads to an increase of at least 62 % on the temperatures of the HS in different levels as compared to unglazed cavity setup. This difference may be attributed to the fact that the glazing decreased convective and radiactive heat loss from the cavity.
The storage is a biphasic system comprising rock pebbles and air.

Some assumptions can be adopted here, namely one-dimensional heat flow, no temperature gradients within rock particles and air is only heated by thermal energy from the rocks either reflected or by convection. The heat absorbed by the container is also neglected and the walls of the storage, but the open parts, are adiabatic.

During the performed tests in the present system, two stages can be distinguished:

1. The Storage is being illuminated by the system of lamps:

During this stage, it can be said that, heat flux impinges directly on the rocks surrounding the cavity (directly or after is transmitted by borosilicate glass cover) and is absorbed by the rocks..Then, as a consequence of heat absorption the temperature of rocks is raised. From there, heat is transferred to the flowing air at the cavity by convection. The air is heated as it goes through the voids in the bed thereby interacting with hot rock pebbles. Then, it is cooled when it faces the uppermost rock pebbles, which are at relatively low temperature, by convection. Thus, energy is gained by the rock pebble system by absorbing heat flux and is lost to the air by convection through the top open side of the storage. Energy balance equation can be written as:

$$m_{rP}c_{rP}\frac{dT_{rP}}{dt} = \alpha_{rP}qA_{cav} - h_{rP}A_r\left(T_{rP} - T_{airb}\right) \qquad \text{(eq.11)}$$

The air in the storage gain heat from heat reflected at rock pebbles, radiation and convection heat transfer from rock particles and loses energy to the surrounding at the open top of the storage by convection:

$$m_{air}c_{air}\frac{dT_{airb}}{dt} = f_{ab}\left(1 - \alpha_{rP}\right)qA_{cav} + h_rA_r\left(T_{rP} - T_{airb}\right) - \dot{m}.c_{air}\left(T_{airb} - T_{sur}\right) \qquad \text{(eq.12)}$$

2. System of lamps is turned-off:

In this stage, cold air enters the storage through the cavity and absorbs heat from the rock pebbles:

$$m_{rP}.c_{rP}\frac{dT_{rP}}{dt} = -h_{rP}A_r\left(T_{rP} - T_{airb}\right) \qquad \text{(eq.13)}$$

$$m_{air}c_{air}\frac{dT_{airb}}{dt} = h_{rP}A_r\left(T_{rP} - T_{airb}\right) - \dot{m}c_{air}\left(T_{airb} - T_{sur}\right) \qquad \text{(eq.14)}$$

## 5. Conclusion

The potential of a natural convection based and direct illuminated rock bed heat storage has been experimentally investigated. A solar simulator comprising 7 halogen lamps and a solar concentrator coupled to the lamp system to focus the light flux to a storage cavity located at the bottom side of the storage have been used during the experiment.

The experiments were done in two different conditions. In one setup the cavity was not covered and the concentrated light flux went through the cavity and thermally interacted with the rock pebbles. In the other, the storage cavity was covered with a borosilicate glass, with 5 cm gap left to let the air go through.

Temperatures at three different positions within the storage were monitored using type-k thermocouples.

In both setups temperatures at the top part of the storage (air exit) are suitable for the intended applications, with even good performance with the borosilicate cover at the cavity, representing 62 % increase as compared to the levels of temperature achieved with uncovered cavity. However, further experiments need to be done with the heat storage integrated to the solar concentrator and a drying system or space to be heated in order to assure the performance of the system.

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## List of Symbols:

| **Symbol** | **Quantity** |
|---|---|
| $c_{rP}$ | Specific heat of rock pebbles |
| $\alpha_{rP}$ | Absorptance of rock pebbles |
| $A_{cav}$ | Area of Cavity |
| $A_r$ | Area of rocks |
| $c_{air}$ | Specific heat of air |
| $h_{rP}$ | Heat transfer coefficient rock-air |
| $T_{rP}$ | Temperature of rock pebbles |
| $T_{airb}$ | Temperature of the air in the rock bed |
| $T_{sur}$ | Temperature of the surrounding |
| $q$ | Heat Flux |
| $m_{rP}$ | Mass of rock pebbles |
| $m_{air}$ | Mass of air |
| $\Delta z$ | Height difference between air input and air output points |