# Simulation and Performance Evaluation of a Dual - operated Solar Cooking and Drying System for developing Countries

Garba, M. M, and Danshehu, B. G.
Sokoto Energy Reserach Centre, Usmanu Danfodiyo University, Sokoto. Nigeria.

## ABSTRACT:

This paper presents performance evaluation of a dual operated passive solar cooking and drying system for an arid and semi arid region. The system has the ability to utilise a range of thermal storage materials including phase change material (PCM) and other locally available oils as the medium for energy storage. The stored energy could be used as a backup to extend the drying and cooking operation of the system during low solar insolation period and night time.

The system has been tested and evaluated in accordance to the figures of merits viz; stagnation temperature test ($F_1$) and water boiling test ($F_2$) for both cooking and drying applications. The system was further tested using different thermal storage materials including water, vegetable oil, wasted engine oil and selected PCM materials for solar cooking and drying applications. The results have shown that, the system could replace most of the current conventional cooking and drying systems in the arid and semi arid climates, and have ability to provide heat retention for up to 5 hours using 4 litres wasted vegetable and engine oils. The heat retention period could practically be further extended when PCM materials are used as a heat storage medium owing to its latent heat storage capability. Computational Fluid Dynamics (CFD) was used for the performance evaluation, the CFD simulation of the dual operated system have shown the optimum outlet duct positions for drying applications. The computated results have shown that dual operation could be best achieved by positioning the duct air outlet at the middle or a bit lower position of the dual operated passive solar drying and cooking system.

**Keywords:** Solar drying, solar cooking, thermal energy storage.

## 1.0 INTRODUCTION

Fuel-wood has been one of the oldest sources of energy known and used by mankind for centuries. Despite the world technological breakthrough and widespread reliance upon fossil fuel among the industrialised nations, fuel-wood has continued to be the dominant cooking energy source used in the developing world. Due to the increasing population in the developing countries, demand for both wood and agricultural land has risen to such an extent that there is now a net depletion of wood resources with a serious consequences such as desertification, soil erosion, food shortage as well as fuel wood shortage. The use of solar cookers is one way of reducing the demand for firewood, coupled with the abandon solar resources in most of these Countries. [Schwarzer et al, (2008)].

In the developing countries more than 80% of the populace lives in the rural areas where up to 90% of the energy being consumed comes from non commercial sources of which fuel-wood is the major energy source. The increasing cost and non availability of conventional energy sources in these areas necessitates exploration of other renewable sources. Fortunately these areas are blessed with abundance solar energy. Passive solar cooking and drying system with thermal heat storage would be an ideal option that would certainly improve the populace's social & economic status, in addition to enormous environmental benefits. According to Michael.et al (2002), Fuel-wood as a dominant energy source for cooking and water heating in the developing world, constitutes to 68%, while animal dung constitutes 13%, Electricity 5%, LPG 1%, Kerosene 2% and Coal constitutes 1% only.

This paper presents the laboratory and CFD simulation evaluation results of a dual-operated passive solar cooking and drying system. The system has the ability to utilise a range of thermal storage materials including phase change material (PCM) and other locally available oils as a medium for energy storage in order to extend its operational period to low solar insolation periods and night

time. This system can store thermal energy inform of sensible or latent heat medium. According to Ahmet Sarı et al (2008); Latent heat thermal energy storage (LHTES) method by phase change material (PCM) is one of the most preferred methods due to its high-storage density and property of storing heat at a constant temperature.
CFD simulation of the model was undertaken in order to asses the effect of the air circulation on the performances of the cooking/drying system. This has been done using the Discrete Ordinance (DO) radiation model in fluent software.

On the other hand Cooking is a reoccurring energy intensive operation used to prepare food for human survival. "The average daily wood consumption in the developing world is 1.3 Kg per person, a family of 5 requires 6.5 kilograms of firewood. [Garba M.M. et al (2008)]

According to Jayaraman et-al (1995), fruits and vegetables losses in developing countries are estimated at 30-40% due to inadequate storage for these perishables food items. The dual operated passive solar cooking and drying system would go a long way in reducing these losses through drying and storing the dried items until the time they are needed.

Similarly, according to 'World Health Organization report, polluted water and sanitation deficiency are the cause of 80% of all the diseases suffered in the developing world. Solar cookers are the only smoke-free solutions mainly for cooking, water distillation and pasteurization.

## 2.0 COMBINED COOKING AND DRYING APPLICATIONS

In different parts of the world, a range of solar cookers were constructed, studied and many were patented. However, their real practical applications is still very limited due to many reasons, such as; unstable climate, single use, economic, cultural, social etc. In order to overcome part of these impediments, a dual operated passive solar cooking and drying system has been developed with thermal energy storage to extend its operation beyond sunshine hours.

The new developed dual operated passive solar system was designed to function as conventional box type solar cooker, and also to operate in its dual capacity as solar drying system. The developed system has an aperture area of 0.40 $m^2$ with a reasonable depth to accommodate a range of cooking pots, and to enable a wide surface area for its solar drying and meat/fish smoking application. The isometric view of the dual operated passive solar cooking and drying system is presented in Figure 1.

The dual operated passive solar cooking and drying system was made into trapezoidal shape which makes the back face of the cooker slightly higher than its front face thus to reduce the shading effects during sun movement and enable drains off condensation / rain showers morning dues precipitates off the glassing. The system can as well perform desalination / distillation for water purification.

For the purpose of solar drying application, two ducts ventilation openings (Air inlet and Air outlet) were provided at the opposite faces of the developed solar cooker shown in Figure 2, to enable cross ventilation when used as a dryer, air passes from the lower part and pass through to take away moisture from the drying specimen and finally moist humid air evaporates and exit at the outlet vent situated at a higher opposite level. In this way, the solar cooker will be able to carry out dual operations of drying and cooking of different household commodities with high moisture content like tomatoes, meat, fish and spices. The air inlet is made at lower position than the outlet to enable optimum utilisation of natural ventilation. These two vents must be kept closed during cooking application of the system.

The solar cooking and drying system can be constructed from varying locally available materials. The system consists of solar collector tray, glazed cover, outer casing and insulation. The system sizing was mainly based on the common available materials. For example, glass and mirror sizes of 0.6m x 0.9m are common in the rural areas. These materials are readily available at affordable cost to most families in the developing world. Insulation plays a significant role in retaining the generated thermal energy; therefore, materials with lower U-value should be used. For this work, a polythene packaging material was used because it is recyclable, non-toxic and light weight. Plywood was also used on the system outer casing. This served as part of the system insulation that retains the collected radiation. A minimum insulation of 5cm was provided for all the sides and bottom walls of the collector. Gloss paint or water resistant material was used to protect the wood against the weather.

The developed dual operated system also incorporated an 8 litres capacity thermal energy storage tank also shown in Figure 2. Both sensible and PCM latent heat storage materials could be used in storing excess heat energy for use at later time, when the sun declines.

## 3.0 SOLAR COOKING AND DRYING PERFORMANCE EVALUATIONS

### (a) Drying performances tests:

Solar drying application of the dual operated passive solar cooker was first tested without thermal storage using a simulated radiation intensity of 500W/m$^2$. The system air temperature stagnation test shown in Figure 3 indicate 23°C, 24°C and 80°C for Ambient air ($T_a$), Air-inlet ($T_i$), and Air-outlet temperatures ($T_o$), respectively. The air inlet was almost equal to the ambient temperatures with a difference of only 1°C.

When 4 litres of water ($H_2O$) was used in the storage tank, air outlet temperature drops from 80°C to 72°C as shown in Figure 4. The inlet and ambient temperatures remain the same as above, showing a 48°C temperature difference. Also when the sensible heat storage material (water) was further increased to 8 litres of water in the storage tank, the outlet air temperature further dropped to 62°C as shown in Figure 5.

The initial solar cooking performance test was conducted using a transparent plastic utensil. Parboil basmati rice and water of 0.70 kg was cooked under a simulated solar radiation intensity of 500W/m$^2$. The cooking specimen (rice) was washed and then a proportion of water was added at 1:2 ratio and then placed directly into the cooker. The rice got cooked at a temperature range from 82°C to 95°C in 3 hrs time with a maximum cooking pot temperature of 95°C as shown in Figure 6.

Secondly a stainless steel cooking pot was used to evaluate the cooking performance of the developed solar cooker. The metallic cooking pot of 200mm diameter and 100mm height had partially transparent lid cover. This enabled physical observation of the cooking process in addition to the measuring transducers. Three different cooking pots were used to assess the cooking performance of the dual operated solar cooking and drying device. Figure 7 shows; (A) The transparent plastic pot, (B) Unpainted metallic pot and (C) Painted metallic pot.

Another cooking test was conducted with unpainted stainless cooking pot under similar condition with the transparent cooking pot as shown in Figure 8.

The system was further tested using different thermal storage materials including water, vegetable oil, waste engine oil and selected PCM materials for cooking. The results, which is shown in Table 1, shows that the system could replace most of the current conventional cooking systems in the arid and semiarid climates, and have ability to provide heat retention for up to 5 hours using 4 litres recycled vegetable and engine oils. The heat retention period could practically be further extended when PCM materials are used as a heat storage medium owing to its latent heat storage capability.

### (b) Cfd Simulation Of Solar Drying Process

The system is envisaged to be used for domestic food crops drying as well as for meat roasting and meat/fish drying applications. These involve optimization of vent positions to enable the realization of effective operating conditions within the system. In this simulation exercise, the initial air in-let vent was fixed at a position as low as possible to enable ambient air entering the drying chamber naturally. The incoming air will pass through the specimen to take up the moisture, enabling the moist air to escape at the out-let vent, which is slightly above the inlet level of the system. Fluent 6.1 is the CFD code employed to evaluate the best optimum vents positions of the dual operated passive solar drying system.

Five cases were tested by gradually changing the vertical position to 20mm above the default position. The results obtained from these five different positions are shown in Figures 9-18. The recorded temperature differences ($\Delta T$) in all five tested CFD cases, were within the functional temperature range that could perform multiple domestic cooking and drying applications as required.

.Comparative results of all the five evaluated cases on air flow pattern of the drying system are presented in Table 2. The average temperatures inside the drying chamber of the system reduce as the duct position is due to air density variation, the air escapes from the system when the vent position is lifted up resulting in more heat loss at the air outlet duct ($T_{out\text{-}let}$) as compared to the lower duct position.

The results have shown a continuous slight temperature increase in the exit ($T_{outlet}$) of the dual operated passive system whenever the outlet vent was moved upwards. The estimated temperature difference between the inlet air and outlet air vents were 51°C (min) and 59°C (maximum) for the evaluated vent size. The recorded temperature differences were all within acceptable range for most domestic crops drying applications. The solar drying system's air flow pattern, showed the need for a drying rack, so that the drying specimens could be lifted slightly above the collector bottom. This would serve two purposes: First, it

enables more convective heat to the drying specimen to facilitate the system drying process; and secondly, it enables better ventilation inside the drying system. The temperature contours of the five CFD simulated cases, showed higher temperatures at the air outlet ducts at higher positions of the drying system. This justifies the use of drying rack placed a little higher from the base for better air circulation and to achieve drying crops items with of high moisture contents like tomatoes. The last cases, i.e. case-4 and case-5 showed better buoyancy air circulation and higher temperature distribution inside the dual operated solar cooking and drying system.

## 4.0 CONCLUSIONS

The developed dual operated passive solar cooking and drying system with phase change material (PCM) storage, if strategically supported and popularised for use in the developing world would bring a huge benefit economically, environmentally and health wise. Most Passive solar thermal energy systems are easily constructed from locally available materials having in mind the economic status of the end users. Reliance on fuel-wood and cow-dung as predominant heating and cooking energy source in the developing world is causing a serious damage to the landscape. Game reserves, thick forests including reserved shelter-belt are fast diminishing. Unsustainable energy use needs careful attention. These are currently neglected by governments and the private sector. Solar thermal energy could be a prominence sustainable means of powering water/space heating, cooking, drying, distillation and ventilation etc. If properly harnessed, especially in the developing world, solar energy would make a tremendous savings economically and environmentally due to the promising abundance and free insolation throughout the year.

Renewable energy sources such as solar energy cannot be depleted for all practical purposes. In contrast to fossil fuels, they are clean sources of energy and do not pollute the environment during process of power generation. It is clear therefore that in the not distant time, renewable energies will dominate the world's energy system, due to their inherent advantages such as mitigation of climate change, generation of employment and reduction of poverty, as well as increased security to the existing energy supplies.

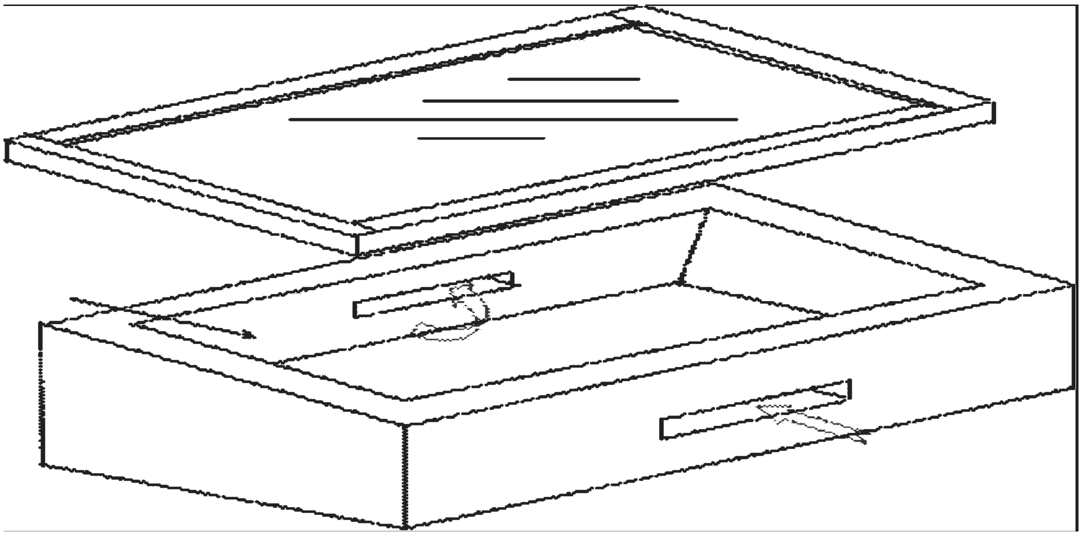

Figure 1: Isometric view of the dual operated solar cooking and drying system

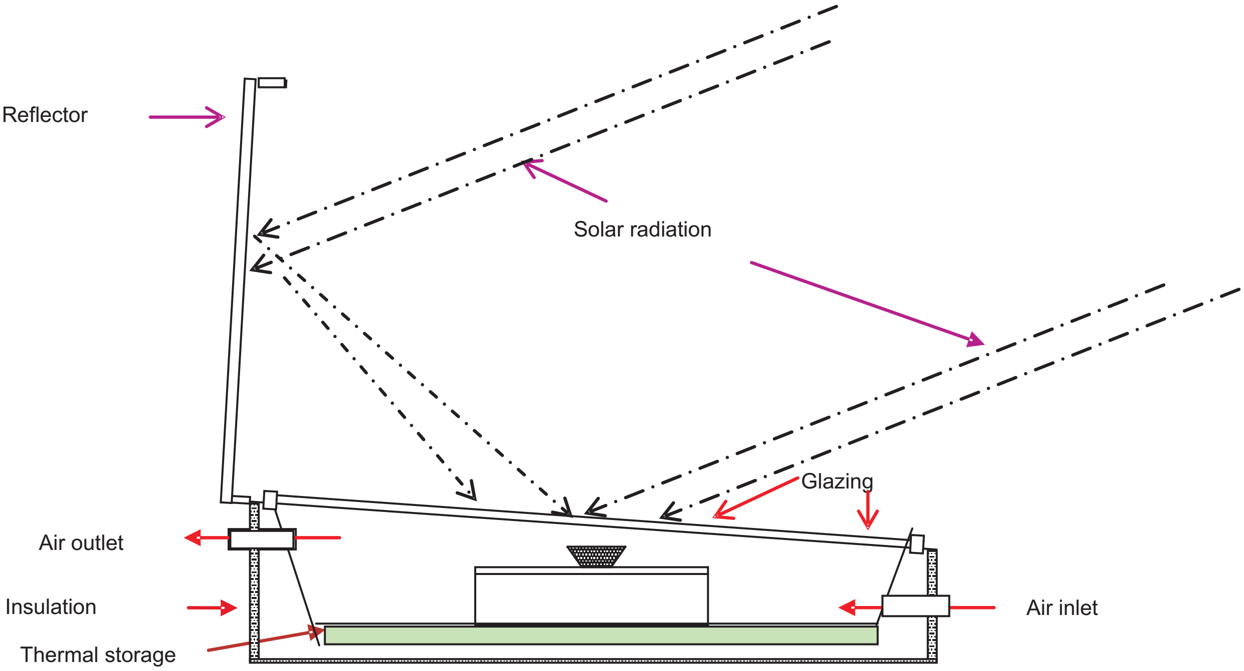

Figure 2: Dual operated (PCM) solar cooker and dryer

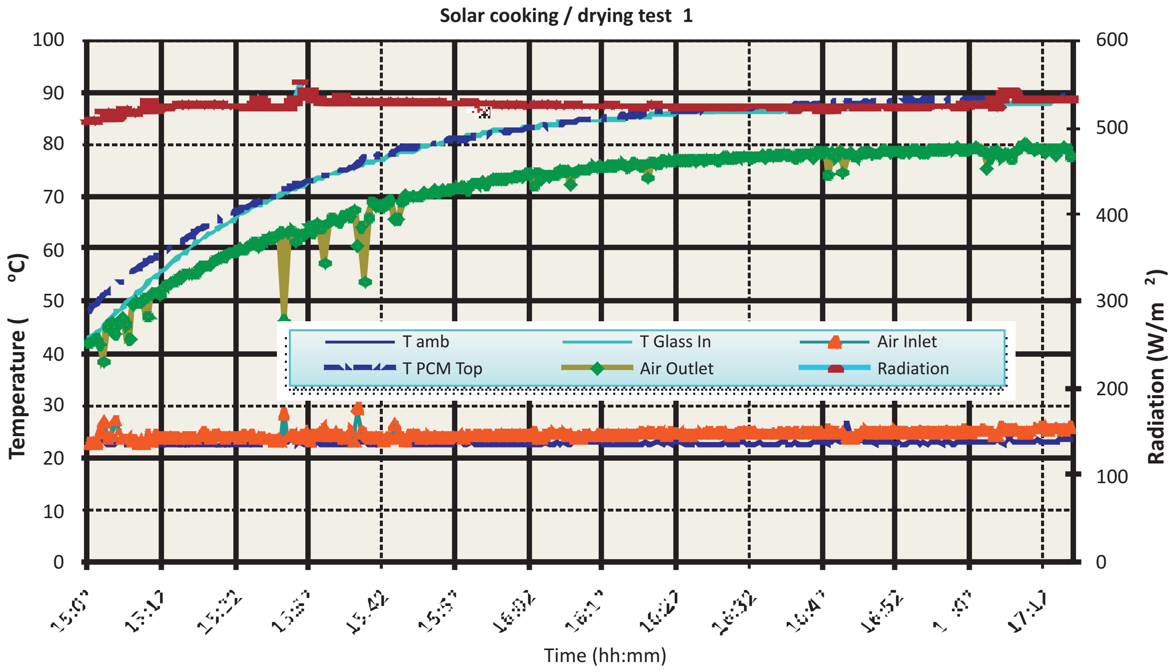

Figure 3: Solar cooking / drying stagnation test 1

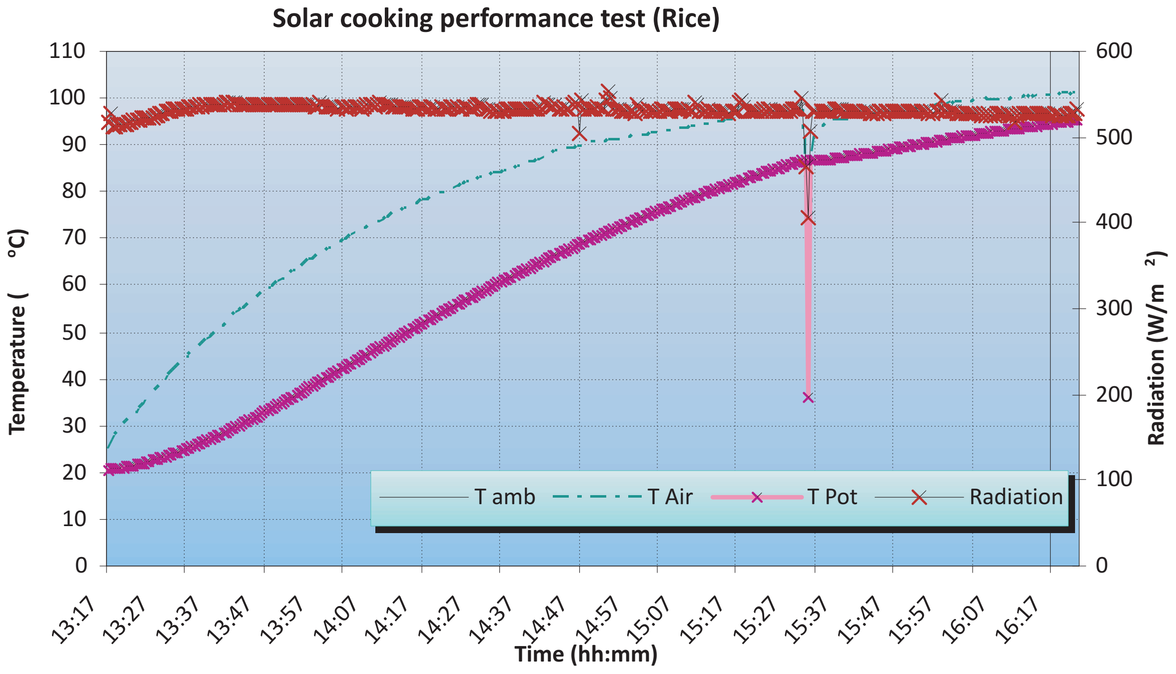

Figure 4: Solar drying stagnation test with 4 litres $H_2O$ sensible thermal heat storage

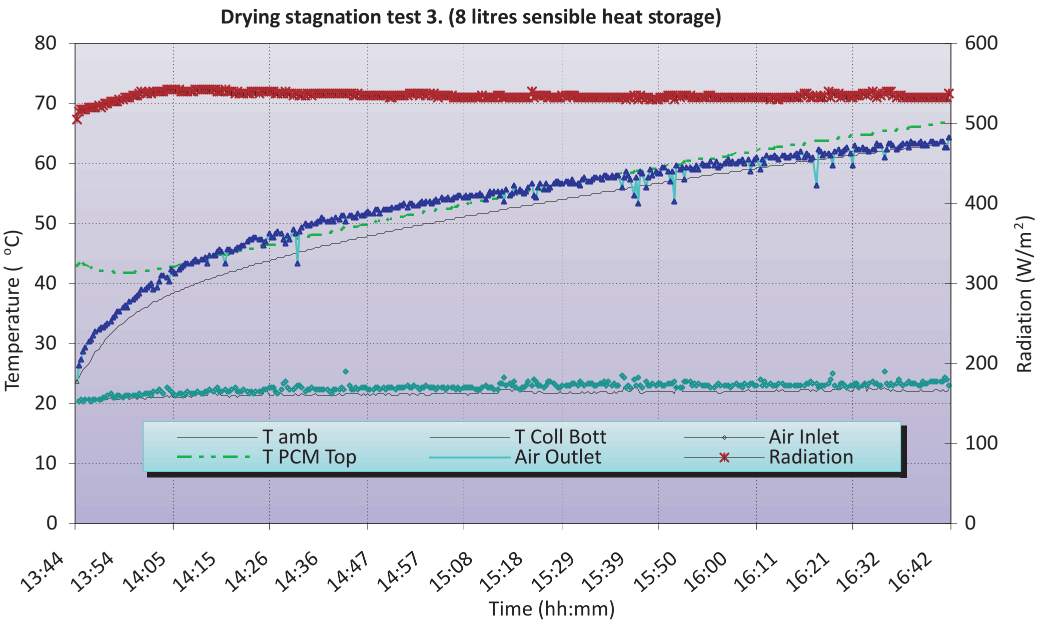

Figure 5: Drying with 8 litres of $H_2O$ sensible heat storage

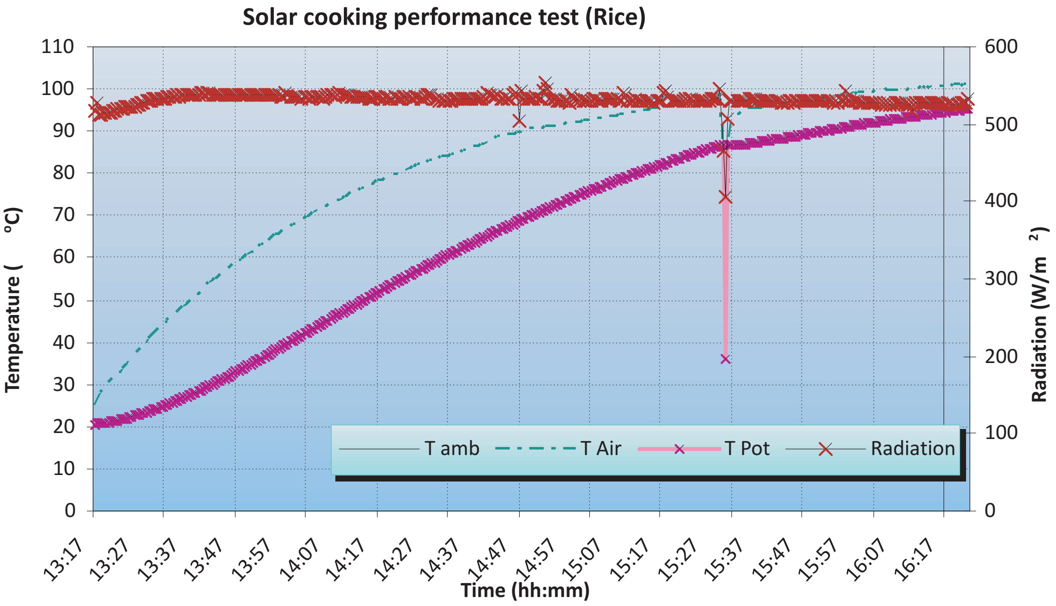

Figure 6: Rice cooking performance test 1

Figure 7: Sample cooking pots used.

Figure 8: Indoor cooking test of the dual operated solar cooking & drying system

Table 1: Cooking Performance Analysis using 4litres ofvarious storage Materials

| Material quantity | Cooking period | Cooling period | Max plate Temp. | Storage Material |
|---|---|---|---|---|
| 4 litres | 3 hr 57min | 4 hrs 40min | 72°C | Water |
| 2 litres | 2 hrs 30min | 5 hrs 25min | 82°C | Organic material. |
| 4 litres | 1 hr 30min | 6 hrs 08min | 82°C | Encapsulated material. |
| 4 litres | 1 hr 30min | 4 hrs 27min | 82°C | Veg. Oil |
| 4 litres | 1 hr 30min | 4 hrs 25min | 83°C | Engine Oil |

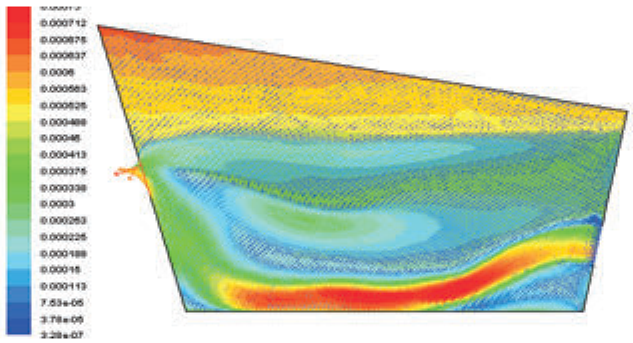

Figure 9: Case -1 Velocity vectors ($m^2$) with outlet vent duct 100 mm above the lower vent

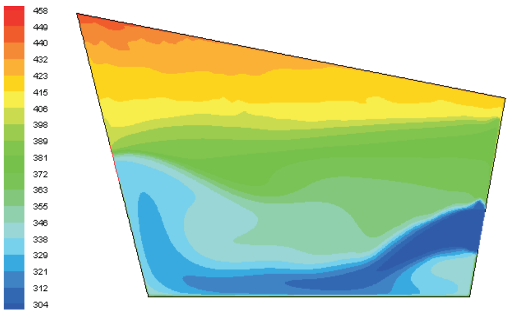

Figure 10: Case -1 Contour of the statistic temperatures (k)

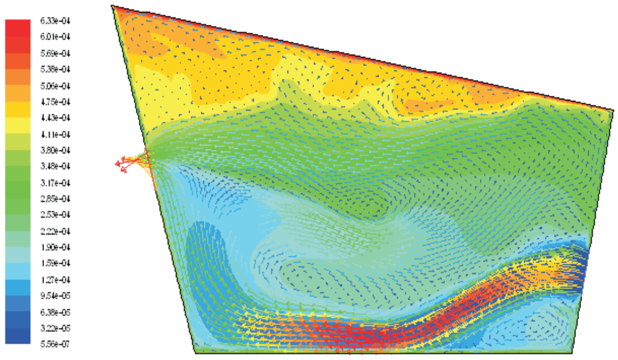

Figure 11: Case-2 Velocity vectors ($m^2$) with outlet vent duct 120 mm above the lower vent.

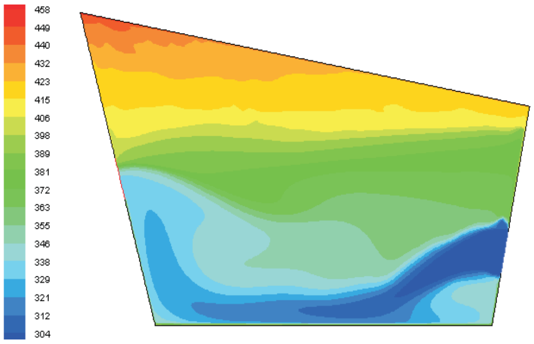

Figure 12: Case-2 Contours of the statistic temperatures (k)

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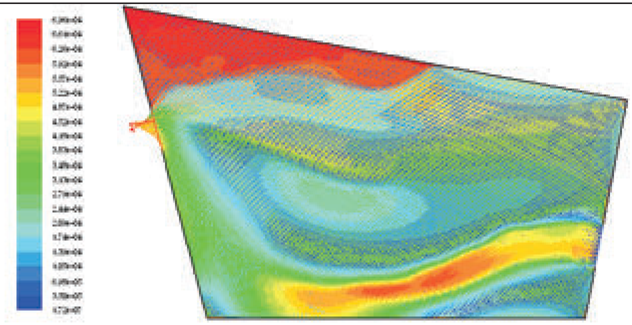
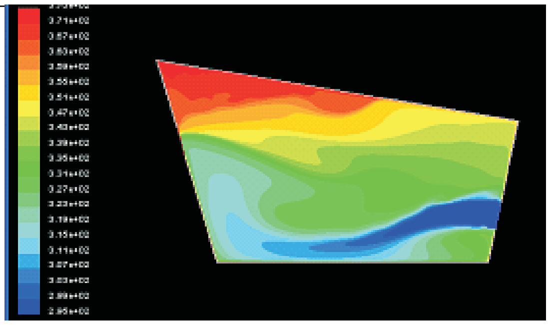
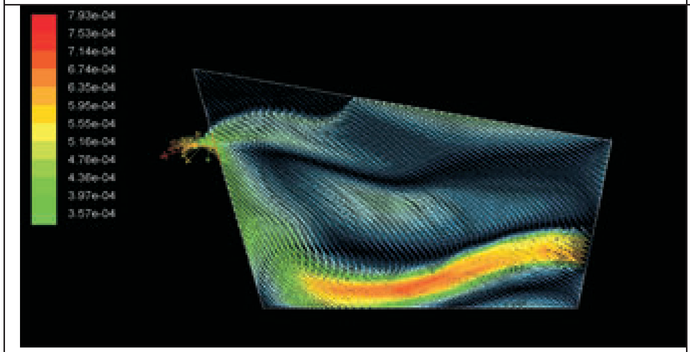
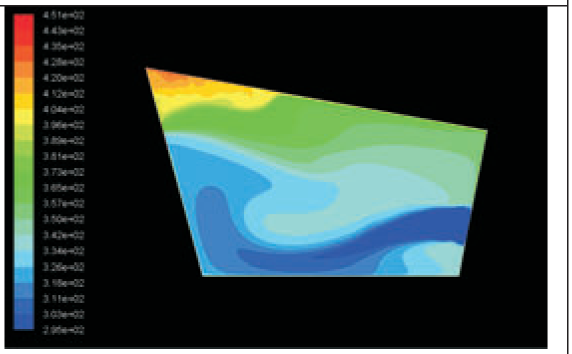
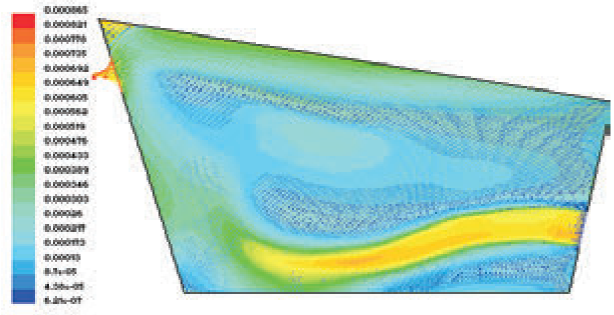
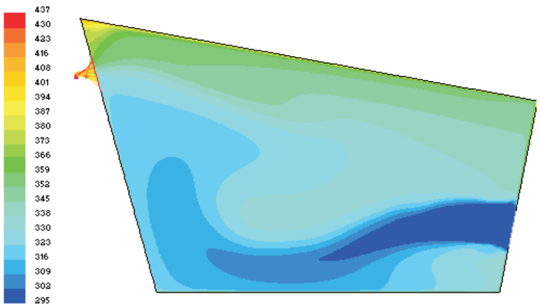
|---|---|
| Figure 11: Case-2 Velocity vectors (m $^{2}$) with outlet vent duct 120 mm above the lower vent. | Figure 12: Case -2 Contours of the statistic temperatures (k) |
|  |  |
| Figure 13: Case - 3 Velocity vectors (m $^{2}$) drying with outlet vent duct 140 mm above the lower vent | Figure 14: Case-3 Contours of the statistic temperatures (k) |
|  |  |
| Figure 15: Case-4 Velocity vectors (m $^{2}$) with outlet vent duct 160 mm above the lower vent. | Figure 16: Case - 4 Contours of the statistic temperatures (k). |
|  |  |
| Figure 17: Case - 5 Velocity vectors (m2) application with outlet vent duct 220 mm above the lower vent. | Figure 18: Case -5 Contours of the statistic temperatures (k). |

Table 2: Comparative performances of the air flow patterns of the drying systems

| *Air Outlet Duct position* (mm) | *T Inlet air* T $_{Inlet}$ ($^oC$) | *Outlet air* T $_{Out-let}$ ($^oC$) | *Inside average air* T $_{Inside}$ ($^oC$) |
|---|---|---|---|
| 100 | 22 | 73 | 93 |
| 120 | 22 | 77 | 79 |
| 140 | 22 | 78 | 70 |
| 160 | 22 | 79 | 68 |
| 220 | 22 | 81 | 65 |

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