A Thermal Model of a Solar Cooker with Thermal Energy Storage using Computational Fluid Dynamics

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Abstract

In this paper, a thermal model of a solar cooker with thermal energy storage (TES) cooking unit is developed. The solar cooker is a parabolic dish concentrating cooker. To allow cooking during hours with limited or no sunlight, thermal energy storage material is integrated in the cavities of the cooker. Sunflower oil is used both as thermal storage material and cooking fluid. As this oil is a fluid, computational fluid dynamics (CFD) was used to model the fluid flow and heat transfer within the solar cooker. The model was validated with experiments and comparison shows that the RMS error between experiments and simulations was around 2%. The fluctuating solar flux in the experiments was the main reason for this deviation. With the validated model, the physics of the charging of the TES and its interaction with the cooking pot is studied. During the beginning of the process, heat is transferred to the TES by conduction through the bottom and sidewalls. When the TES is heated up, the dominant heat transfer mechanism becomes natural convection, which transports the heat from the TES towards the cooking pot. This natural convection induces a fairly uniform temperature profile in both the TES and the cooking pot. With an incoming solar power of 4750 W m^2, a steady state temperature of 409.8K in the TES, and 405.8 K in the cooking pot can be reached within 4 hours. The maximum temperatures are very close to those observed in the experiments (410.9 K for the TES and 406.8 K for the cooking pot), and these temperatures are sufficiently high to cook or bake various food items.

Keywords: Solar Cooker, Thermal Energy Storage, Computational Fluid Dynamics,

1. Introduction

The use of solar cookers eliminates the usage of traditional fuels such as coal or wood and reduces greenhouse gas emissions. The most efficient type of solar cooker in terms of the shortest cooking time and the highest cooking temperature is the parabolic dish solar cooker. Cheap and efficient designs of parabolic dish solar cookers for developing countries have been investigated recently (Ahmed et al., 2020; Mohod et al., 2010). However, a major drawback of these solar cookers is that they cannot be used when the sunlight is limited or even not available, for instance at night or during cloudy periods. To cater for this drawback, thermal energy storage (TES) systems can be integrated with solar cookers so that off-sunshine cooking can be possible (Mbodji and Hajji, 2017; Mawire et al., 2020). The two main options for TES for solar cookers are indirectly storing the thermal energy in a storage tank using a heat transfer fluid (HTF) or storing the thermal energy directly in the cooking pot. The latter seems to be more economically viable since the use of fluid circulating pumps and pipes is eliminated. Plenty experimental studies have been performed to optimize the design of these solar cookers, to choose the most appropriate materials for the TES and to study the cooking performance (Vigneswaran et al., 2017; Wollele and Hassan, 2019; Mawire et al., 2020). Nevertheless, some of the authors have suggested the use of a numerical model for performance enhancement and optimization. In particular, experimentally validated computational fluid dynamics (CFD) tends to provide detailed insight of the fluid flow and heat transfer mechanisms. Studies on CFD models for cooking processes are rather limited (Joshi et al., 2012; Kumaresan et al., 2015; Mbodji and Hajji, 2017; Abreha et al., 2019), thus it is essential to develop models that can be used to enhance and optimize the performance of solar cooking storage pots that can be used for off-sunshine cooking hours. Therefore, the aim of the paper is to develop such a CFD model for a solar cooking storage pot for performance enhancement and optimization. The novel aspect of the study is the use of vegetable oil as TES, promoting a greener environment and a cheap sustainable cooking solution for developing countries. Few studies have appeared in recent literature on solar cooking pots using vegetable oils, and the results

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Fig. 1: Photograph of the parabolic dish solar cooker with TES system implemented in the cooking pot. Left: parabolic solar collector, right: cooking pot with TES system

presented will provide invaluable information on the design and heat transfer mechanisms of these cooking pots. After model validation with experiments, a detailed study on the heat transfer characteristics and performance parameters is done, including the transient charging process of the TES and the steady state temperatures in both the TES and cooking pot.

2. Numerical model

The solar cooker used in this work is based on the parabolic dish solar cooker used in the study of Mawire et al. (2020). A photograph of this setup is shown in figure 1. The solar light is concentrated by a parabolic dish with a diameter of 1.2m and focussed on the bottom of a cooking pot. In this study, only the cooking pot with TES system is modelled and the parabolic collector is substituted by a solar heat flux input at the bottom of the pot. A schematic view of the pot geometry is shown in figure 2. The cooker is axisymmetric with the x-axis as symmetry line and the radius is $R_c = 0.16$m and the height $H_c = 0.11$m. The cooker consists of two compartments: one for the thermal energy storage (TES) system on the bottom with a height H = 3.2cm and one for the cooking fluid in the middle (called the cooking pot) with a radius R = 0.125m. The walls of the cooker (represented by the thick black lines) are made of stainless steel and have a thickness of 3mm. For both compartments, sunflower oil is used as the heat transfer fluid. The volume of oil in the TES system is 3.75 liters and for cooking, a mass of 0.5 kg oil is used.

As both the TES and cooking pot consist of a mixture of oil and air, Computational Fluid Dynamics (CFD) is used to model the heat transfer and associated natural convection within both volumes. The equations governing the fluid flow are given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0, \qquad \text{(eq. 1)}$$

for the continuity equation and

$$\rho(\frac{\partial \boldsymbol{V}}{\partial t} + \boldsymbol{V} \cdot \nabla \boldsymbol{V}) = -\nabla \mathrm{p} + \nabla \cdot \left(\mu(\nabla \boldsymbol{V} + (\nabla \boldsymbol{V})^{\boldsymbol{T}}) - \frac{2}{3}\mu(\nabla \cdot \boldsymbol{V})\boldsymbol{I}\right) + \rho \boldsymbol{g}, \quad \text{(eq. 2)}$$

for the momentum equation, where ρ (kg m^{-3}) is the density of the fluid, $\boldsymbol{V}$ (m/s) is the velocity vector, μ (kg m^{-1} s^{-1}) the dynamic viscosity, p (Pa) the pressure, $\boldsymbol{I}$ the unity tensor and $\boldsymbol{g}$ (m s^{-2}) the gravitational acceleration. In each compartment, a mixture of oil and air is present. To capture the free surface between them, the volume of fluid method is used (Hirt and Nichols, 1981). The material properties of the sunflower oil, like density, heat capacity, viscosity and thermal conductivity are temperature dependent and taken from the studies of Mawire et al. (2020), Fasina and Colley (2008), Cancaim (2012) and Hoffmann et al. (2018).

The boundary conditions are estimated from the work of Mawire et al. (2020). At the bottom of the cooker, a constant heat flux of 4950 W m^{-2} is applied, which corresponds to the average solar flux measured in the experiments. The

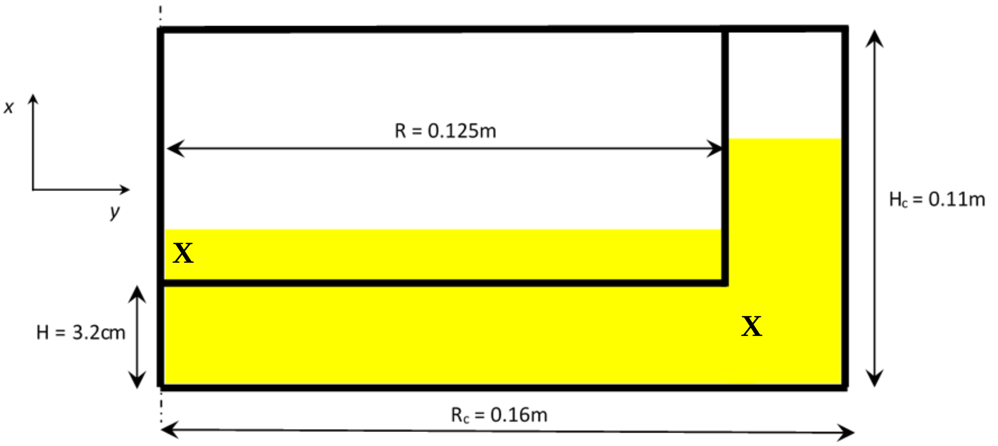


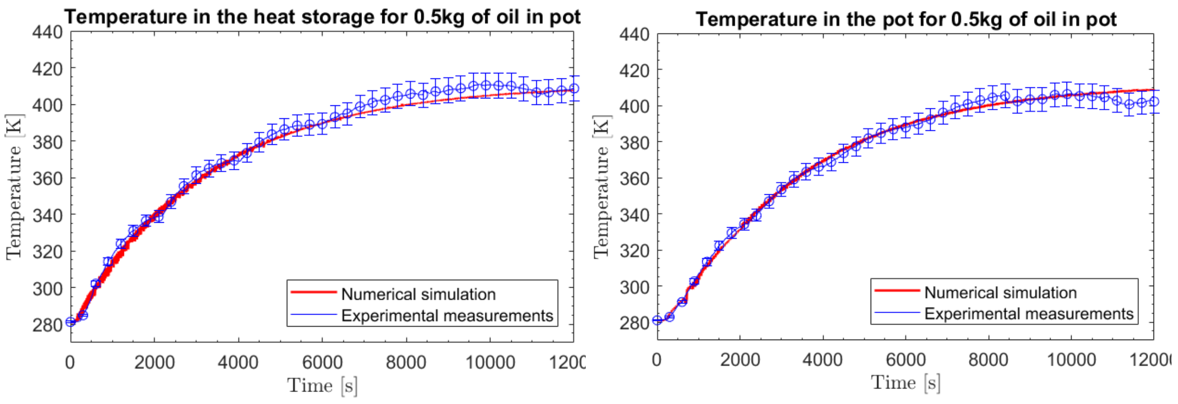
Fig. 2: Schematic view of the geometry of the solar cooker with a TES system. The X's denote the locations of the temperature measurements for validation

heat losses through the top and side walls are modelled as a combination of convective and radiation heat fluxes. The corresponding parameters are determined from the experiments, which give an average heat transfer coefficient h = 26.5 W m^{-2} K^{-1}. As the pot was painted black, the emissivity is chosen to be 1.

All governing equations for the gas and liquid phase were solved simultaneously using the pressure-based finite-volume solver ANSYS Fluent. For convective and diffusion terms, a second-order upwind discretization scheme was used. The PRESTO! interpolation scheme was adopted to obtain the pressure at the cell faces. The temporal derivative is discretized using a second order implicit scheme. A grid study using three different mesh sizes, coarse = 48.024 cells, medium = 216.512 cells and fine = 768.384 cells, shows that the results of the medium mesh are within 0.3% of the fine mesh and therefore the medium mesh is chosen in this study. To study the influence of the temporal discretization, 3 different timesteps (1, 0.5 and 0.25s) were adopted and the results of 0.5s where within 0.5% of the smallest time step and hence this timestep was chosen in the simulations.

3. Experimental validation

The numerical simulations are validated by thermocouple measurements at two locations in the cooker (denoted by the X's in figure 2) in the study of Mawire et al. (2020). Temperature measurements were taken every 30 seconds and the temperature evolution is shown in figure 3. Initially, the oil heats up very fast reaching a temperature of around 366K in the TES and 363K in the pot in the first hour. Afterwards, the temperature increase is slower and the varying experimental conditions have more influence on the temperature profile. Nevertheless, the CFD simulation is within measurement accuracy of the experiments for all timesteps. The RMS error between experiments and simulations was around 2%, and is mainly attributed to the fluctuating solar flux in the experiments. In the simulations, an average flux was implemented as boundary condition, which means that transient flux variations, like for instance found in the temperature decrease in figure 3 near the end, are not incorporated in the simulations. Hence, the CFD model is considered to be adequate in predicting the transient heat transfer in the cooking pot.


Temperature in the heat storage for 0.5kg of oil in pot

Temperature in the pot for 0.5kg of oil in pot

Fig. 3: Validation of the numerical simulations with the experiments of Mawire et al. (2020)

4. Heat transfer mechanisms

4.1 Transient heating

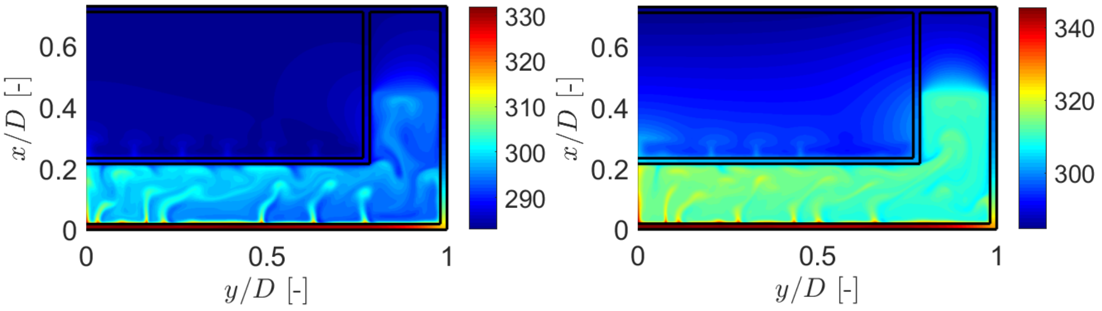
With the validated CFD model, the different heat transfer mechanisms can be studied in the heating process of the solar cooking pot. Figure 4 shows the temperature distribution in the cooker at different time instants. At the beginning, the bottom of the pot is heated by the solar radiation flux and this heat is transferred to the oil of the TES by conduction. The density and viscosity of the oil near the bottom decrease which creates buoyancy forces and less viscous resistance and hence hot oil is convected upwards. This induces Rayleigh-Bénard convection cells (figure 4a). These cells are the main heat transfer mechanism from the bottom of the cooker to the oil. Their regime is governed by the Rayleigh number, which is given by

$$Ra_L = \frac{g\beta}{\nu\alpha}(T_b - T_u)H^3, \qquad \text{(eq. 3)}$$

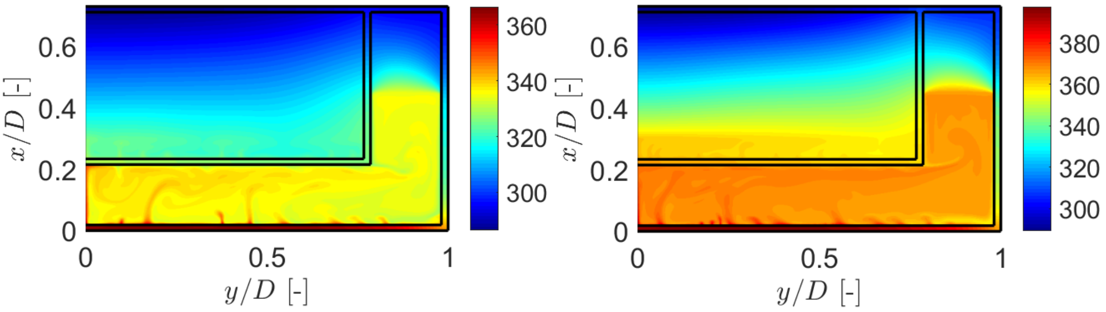
where β (6.9858x10^{-4} K^{-1}) is the thermal expansion coefficient (Canciam, 2012), ν (2.4854x10^{-5} m^2 s^{-2}) the kinematic viscosity, α (8.5283 x 10^{-8} m^2 s^{-1}) the thermal diffusivity, T_b (330 K) the temperature of the bottom and T_u (281 K) the temperature of the top. The properties of the oil are taken at an initial temperature of 281K. At the start, the Rayleigh number is equal to 5.1913x10^6. The Grasshoff number,

$$Gr = \frac{g\beta}{\nu^2}(T_b - T_u)H^3, \qquad \text{(eq. 4)}$$

is equal to 1.7814x10^4, which means that the natural convection is in the turbulent regime. As the oil heats up further, figure 4b, these Rayleigh-Bénard convection cells also appear in the oil in the cooking pot. As the temperature at the bottom of the cooking pot is lower, these convection cells are weaker than the ones in the TES. Due to convection, the oil on both the TES and cooking pot heat up quite uniform as shown in figures 4c and 4d.



(a) Temperature profile after 450 seconds. **(b) Temperature profile after 900 seconds.**



(c) Temperature profile after 1800 seconds **(d) Temperature profile after 3600 seconds.**

Fig. 4: Temperature (K) profiles in the cooking pot at different time instants

4.2 Steady state

The steady state temperature profile is shown in figure 5, and it is reached after about 4 hours. The average temperature at the bottom of the TES is 427.2 K and at the bottom of the cooking pot, it is 406.5 K. The average oil temperature in the TES is 409.8 K and the temperature distribution is very uniform due to the natural convection. Inside the cooking pot, the average temperature is 405.8 K and it is also very uniform. These temperatures are very close to the ones observed in the experiments (410.9 K for the TES and 406.8 K for the cooking pot) and are sufficiently high to cook or bake various food items.

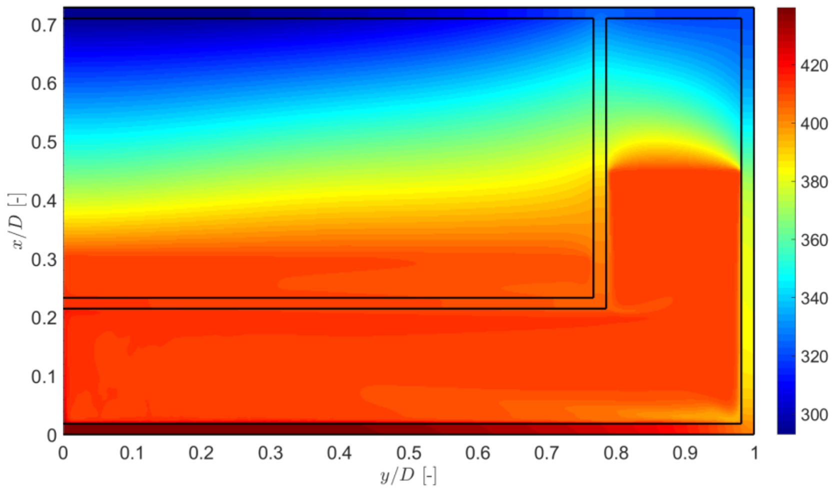


Fig. 5: Steady state temperature profile

5. Conclusions

In this paper, a thermal model of a solar cooking pot has been developed and validated using computational fluid dynamics (CFD). Comparison with experiments shows that the resemblance between the two is within measurement accuracy and differences are attributed to solar flux variations in the experiments. With the numerical model, the physics in the heating of the cooker is studied. At the beginning, the main heat transfer mechanism is natural convection in the TES system, which creates a fairly uniform temperature profile. After 4 hours, a steady state temperature of 405.8K in the cooking pot is reached, which is sufficiently high to cook all sorts of food and vegetables. With the newly developed model in this study, solar cooking pots with integrated TES systems can be further optimized towards heat transfer, maximum temperature and warming up time.

6. Acknowledgments

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