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Inlet Size and Location Impact on Greenhouse Dryer Process Dynamics

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A significant amount of food waste is generated in the post-harvest stage of the food production chain due to unsuitable drying. Understanding greenhouse dryer (GHD) process dynamics could help achieve a better dryer design to reduce food waste generation. This study utilizes a Computational Fluid Dynamics (CFD) model of a GHD to investigate the effect of inlet size and location on GHD kinetics. The software used is COMSOL software (COMSOL Multiphysics version 5.6) which is capable of modeling the GHD. From the simulation results, three key observations in terms of GHD dynamics are derived. The inlet size is positively correlated to the average velocity in GHD and negatively correlated to the average temperature in GHD. The inlet location impacts both the spatial distribution of the temperature and velocity in the GHD. This implies that a GHD operating temperature and drying rate can be controlled with a simple modification of inlet size and location, which means a single GHD could be used to dry different crops depending on the season. It is concluded that the inlet size and location should be considered when designing a GHD.

1. Introduction

For agricultural products to be preserved and to meet international market quality standards drying is a necessary process. GHD is a low-cost simple drying facility that utilize solar energy for the drying of agricultural products, which makes them globally accessible for small-scale farmers (Udomkun et. al., 2020). Since the quality of fruit and vegetables are very sensitive to the drying temperature, air velocity, and other drying parameters (Getahun et. al., 2021), dryers need to be tailored for each fruit and vegetable to minimize waste generation. Unfortunately, researching these parameters experimentally is time-consuming and expensive (Abderrahman et. al., 2021). There is a silver lining that GHD (and other dryer types) can be modeled using the (CFD) technique (Getahun et. al., 2021).
For example, Chaven et. al. (2021), optimized a compact solar grain dryer design for higher thermal energy efficiency via CFD simulations by manipulating the size and location of the solar fan. Recent studies focus on the experimental analysis of dryer performance, while there are CFD techniques that focus on a micro level, which means that the modeling was conducted on a fruit and vegetable scale (Getahun et. al., 2021). However, the performance of the dryer, such as thermal efficiency and airflow, has a significant effect on drying rate and kinetics and should be considered (Getahun et. al., 2021). Furthermore, designing an energy-efficient GHD design for a specific crop and climate is another major challenge Chauhan and Kumar, 2018).
Simulation and modeling of GHD via CFD are recommended for faster and more accurate results at a lower cost (Sahdev et. al., 2016). Therefore, this study aims to fill the gap in understanding dryer kinetics inside GHD by utilizing the CFD technique to focus on the effect of inlet size and location at the GHD process dynamics. The new finding in this work is the use of COMSOL software (COMSOL Multiphysics version 5.6) to simulate a GHD on a macro level of the study.

1.1 Brief look at greenhouse dryer design aspects

GHD are an affordable, cost-effective, and energy-efficient option for drying agricultural products (Srinivasan and Muthukumar, 2021). Therefore, numerous experimental investigations have been carried out on the GHD.

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Table 1 briefly mentions the Greenhouse Dryer design aspects that have been investigated experimentally in the open literature.

Table 1: Greenhouse dryer design aspects (Sigh et. al., 2018)

Design based on	Example
Heat transfer	Direct or mixed mode
Air flow	Active (forced convection) or passive (natural convection) mode
Type of floor	Concrete, gravel, or rock bed floor
Cover material for greenhouse	Polythene, polycarbonate, or glass
Roof shape	Even span, parabolic or trapezoidal
Use of north wall	Insulated north wall or reflecting north wall
Thermal storage material	Black-painted concrete floor or solar collector

Other design aspects of GHD include the integration of sustainable technology such as Solar panels connected to Electric fans. Structural design of a GHD such as dimensions (length, width, and height), inlet and outlets (size, location, and shape), and shape (parabolic or cuboid shaped GHD) impact the performance of the GHD (Mishra et. al., 2021). However, certain design aspects require capital investment which might not be affordable by small scale farmers, hence an affordable solution has to be inclusive of research. This work studies the inlet size and location impact on GHD average airflow and average temperature under no-load conditions as these two performance parameters directly correlate to the drying performance of a GHD. The inlet location and size are can be practically modified by a small scale farmer, therefore this works aims to find the viability of modifying the inlet size and location of an existing GHD to change its key drying performance parameters such as average temperature (as certain agricultural products are sensitive to temperature) and average airflow (the higher the airflow the higher the drying rate) to suit a drying application without expending monetary and material resources to construct or buy a new GHD. This work is conducted via the CFD technique as explained above, pervious work have already established reliable mathematical models to simulate GHD in no-load and load conditions. This work aims to be a preliminary study of utilizing the inlet size and location to improve and manipulate GHD drying performance as a very cost-effective approach. Furthermore, this work aims to provide the concept of manipulating the inlet (size, shape, location) to control the GHD drying kinetics.

1.2 Computational fluid dynamics and greenhouse dryer

Before constructing any GHD, an accurate estimation of the solar radiation, mass transfer coefficients, and heat transfer coefficient is required (Choab et. al., 2019). CFD tools help in predicting the greenhouse design, air temperature and movement, condensation rate, wind speed, turbulent kinetic energy, solar heat load, transpiration of heat flux density, and recirculation zones (Srinivasan and Muthukumar, 2021). The underlying numerical computation lies with partial differential equations, specifically Naiver-Stokes equations, which are shown below.

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{u} = 0 \tag{1}$$

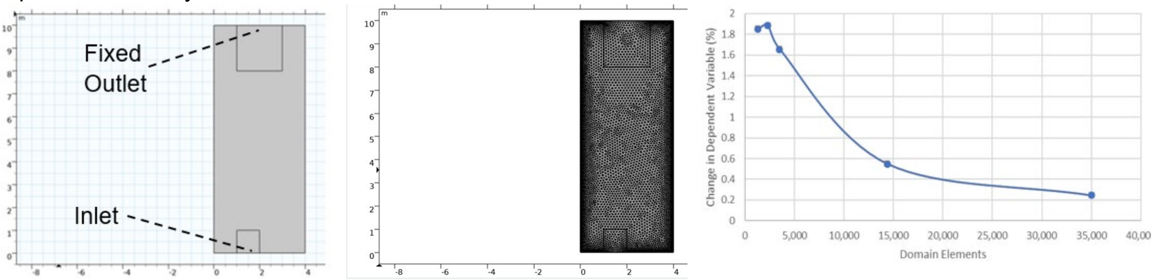
$$\frac{\partial (\rho u_i)}{\partial t} + \nabla \cdot (\rho u_i \vec{u}) = -\nabla p + \rho g \tag{2}$$

$$\rho C_p \frac{\partial T_f}{\partial t} + \rho C_p u_i \nabla T_f = \lambda \nabla^2 T_f + S_T \tag{3}$$

Eq(1), Eq(2), and Eq(3) represent the conservation law of mass, momentum, and energy used to model any dryer. Since this study only considers physical GHD design, the thermal modeling of vegetables and fruits is not discussed, however relevant modeling techniques can be found (Getahun et. al., 2021).

2. Methodology

The CFD software package used is COMSOL Multiphysics software. Due to the computational power limitations, the GHD model is simplified from 3D to 2D as shown in Figure 1. The dimension of the GHD is 4 m x 10 m x 2 m in width, length, and height, the GHD dimension aims to represent the average small scale GHD size found in the open literature. The GHD is assumed to be under no-load conditions to directly investigate the impact of inlet size and location on the GHD performance (average temperature and average airflow), while other parameters are kept constant such as humidity, solar radiation and a constant wind speed. Both the inlet and outlet are rectangular in shape as shown in Figure 1(a), but the outlet has a fixed size and location while the inlet is variable. Figure 1 shows the full schematic layout, the top view, and the mesh structure used for the simulation. The mesh structure is generated by selecting the "Fine" setting in the COMSOL default mesh generator with an output of 14393 domain elements (mesh cells) and 611 boundary elements (mesh cells specifically at the boundary). Figure 1 (c) shows the mesh/grid independency test and 10 000 domain elements has a change of less than 1 percent, therefore the "Fine" setting is more than sufficient to accurately simulate the parametric study. The PARDISO solver is used for this model.



(a) (b) (c)

Figure 1: COMSOL Multiphysics 2D (a) full schematic layout (b) mesh view (c) Mesh dependency test of GHD

This work is computational based only, thus the accuracy and reliability of the results depend entirely on the model and mesh element size used. There have been studies like (He, Et. Al., 2018) who modeled GHD as 2D CFD model using similar foundation of boundary conditions and Naiver-Stokes equation as shown in this paper. Notably, mesh settings used in some of the simulations in this project are less than ideal as the computational power available is limited. The GHD parameters are defined in Table 2, only inlet size and location are variable parameters, and the rest of the parameters remain constant in the study. Hence, solar radiation, wind speed (air inlet velocity), wind humidity (inlet air humidity) and wind temperature (inlet air temperature) are assumed to be constant to investigate the impact of inlet size and location on GHD performance (average airflow and temperature).

Table 2: Greenhouse dryer parameter values

Greenhouse Dryer Parameter	Parameter value
Length (m)	10
Width (m)	4
Height (m)	2
Central Height (m)	2
Cladding Material	Polyethylene cover
Rectangular Inlet Size (m)	From 1 to 2
Rectangular Outlet Size (m)	2
Inlet Location	From 0.5 to 1.5 m away from a side wall
Outlet Location	1 m away from a side wall

As shown in Table 2, the inlet size range is aimed to test the effect of an inlet size increase and decrease on GHD performance. Likewise, the inlet location is aimed to test whether a side inlet (0.5 m or 1.5 m) or a center inlet (1.0 m) is better performing. The GHD model has the following assumptions. Thermophysical properties are assumed to remain constant under varying pressure and temperature as GHD is under no-load conditions, therefore humidity remains constant and the change of temperature is small enough to be negligible. The GHD is assumed to be exposed to 1,000 W/m^2 of solar radiation to replicate a clear sunny day. For initial conditions, the pressure of the GHD is assumed to be 1 atm (101,325 Pa). For boundary conditions, the GHD inlet and surrounding weather is assumed to be 25 °C at 1 atm (101,325 Pa), with a constant inlet velocity of 0.5 m/s to model a constant wind.

3. Results and discussion

3.1 Results

Part of the GHD Process dynamics is the average airflow and temperature inside GHD. The average temperature is the mean air temperature inside the GHD as depicted in Figure 2 (a) and 2 (b). Figure 3 illustrates the results from the simulation at inlet location 0.5 m. Note that "IL" stands for Inlet Location as stated in the nomenclature section. The contour plot distribution for the model is taken at a time of 60 s because it is the point where flow is most stable as denoted in Figure 3 and Figure 4, the variable “in” stands for inlet size, and variable “inp” stand for inlet position.

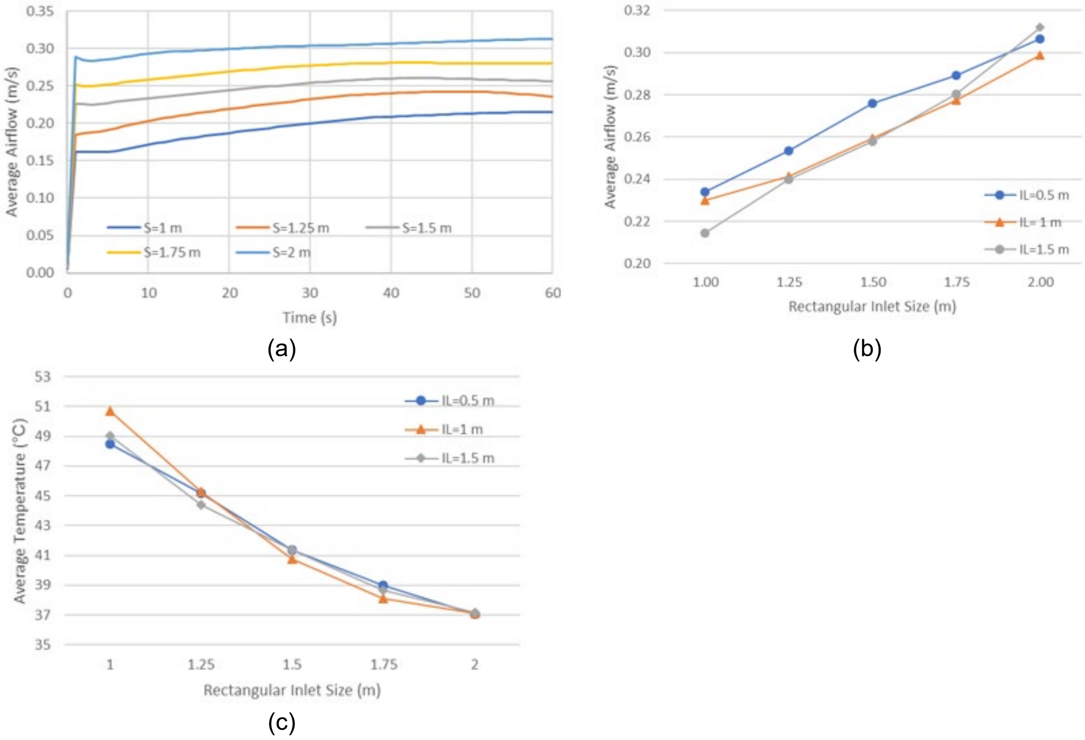


Figure 2: (a) Steady State Test, (b) Average airflow (c) Average temperature in GHD

3.2 Discussion

Figure 2 (a), showcases the average airflow in GHD across 60 seconds. The graph shows the flow stabilises (reaches steady state as the line flattens) in GHD at time 40 seconds and remains constant with small fluctuations as the inlet is modelled to have a constant flow of 0.5 m/s. Therefore, small flow fluctuations are inevitable due to the constant flow of air, but it is clear that the flow stabilizes at 40 seconds and remains steady, hence the readings of Figure 2 (b), 2 (c) and 3, is taken at time = 60 seconds to represent steady state of GHD. The flow inside the GHD is laminar as the GHD size is relatively big and the inlet velocity is at 0.5 m/s.

The first key observation is the average airflow and average temperature are negatively correlated to each other as shown in Figure 2 (b) and 2 (c) because at a higher average airflow there is less residence time for the air to absorb solar radiation inside the GHD resulting in a lower average temperature. The second key observation is the average airflow is positively correlated to the inlet size as shown in Figure 2(b), as a larger inlet size signifies a larger mass flow rate into the GHD. About 30% to 45% increase in average airflow is observed when the air inlet size is doubled depending on the inlet location. This means the average airflow can increase with increasing inlet size at the expense of average temperature and vice versa. This can be used by farmers or GHD operator to directly manipulate the drying rate of a GHD as average airflow and temperature directly impact the drying rate of any agricultural product.

The third key observation is the average airflow is higher when the air inlet is not centered (IL=1 m), however, the correlation between average airflow and inlet location is non-linear. Figure 3 shows that the velocity and temperature distribution from inlet size 2 m to 1 m with constant inlet location of 0.5 m as the location of 0.5 m yields the highest average airflow (generally faster drying rate) within GHD with the varying inlet size as shown in Figure 2(b). From Figure 3 (a), the velocity distribution is negatively correlated to the 3 (b) temperature distribution which agrees with the key observations made from Figure 2 (b) and 2 (c). This can be seen in Figure 3 as high airflow regions are in red contour colour and are low temperature regions are blue contour colour.

Another observation is the average temperature is negatively correlated to the inlet size due to the increased airflow. As the inlet size doubles, the average temperature drops by 11 °C to 13 °C as shown in Figure 2 (b) and 3. In other words, the inlet size can be used to control the temperature inside the GHD to optimally dry any temperature sensitive fruits or vegetables. The average temperature is affected by inlet location in a non-linear way, but more in-depth simulations need to be carried out for a reliable conclusion.

Overall, the inlet location and size affect the spatial distribution of temperature and velocity in the GHD as shown in the Figure 3. From Figure 3, regions with low airflow such as corners have higher average temperature that the rest of the GHD. This is important when it comes to placing drying trays to dry temperature sensitive fruits. These observations give the means to a farmer or an operator to dry different crops by using a single GHD by simply changing the inlet size or location. For example, a farmer wishes to dry rice one season and strawberries the other season. The farmer can use a single GHD to dry both agricultural products by controlling the GHD internal temperature by changing the inlet size as shown by our results. This effectively reduces the capital needed to cost effectively dry two agricultural products for a small-scale farmer and contributes in the reduction of organic waste generation in the post-harvest stage. Therefore, when designing a GHD having variable inlet size and location is very beneficial and should be considered.

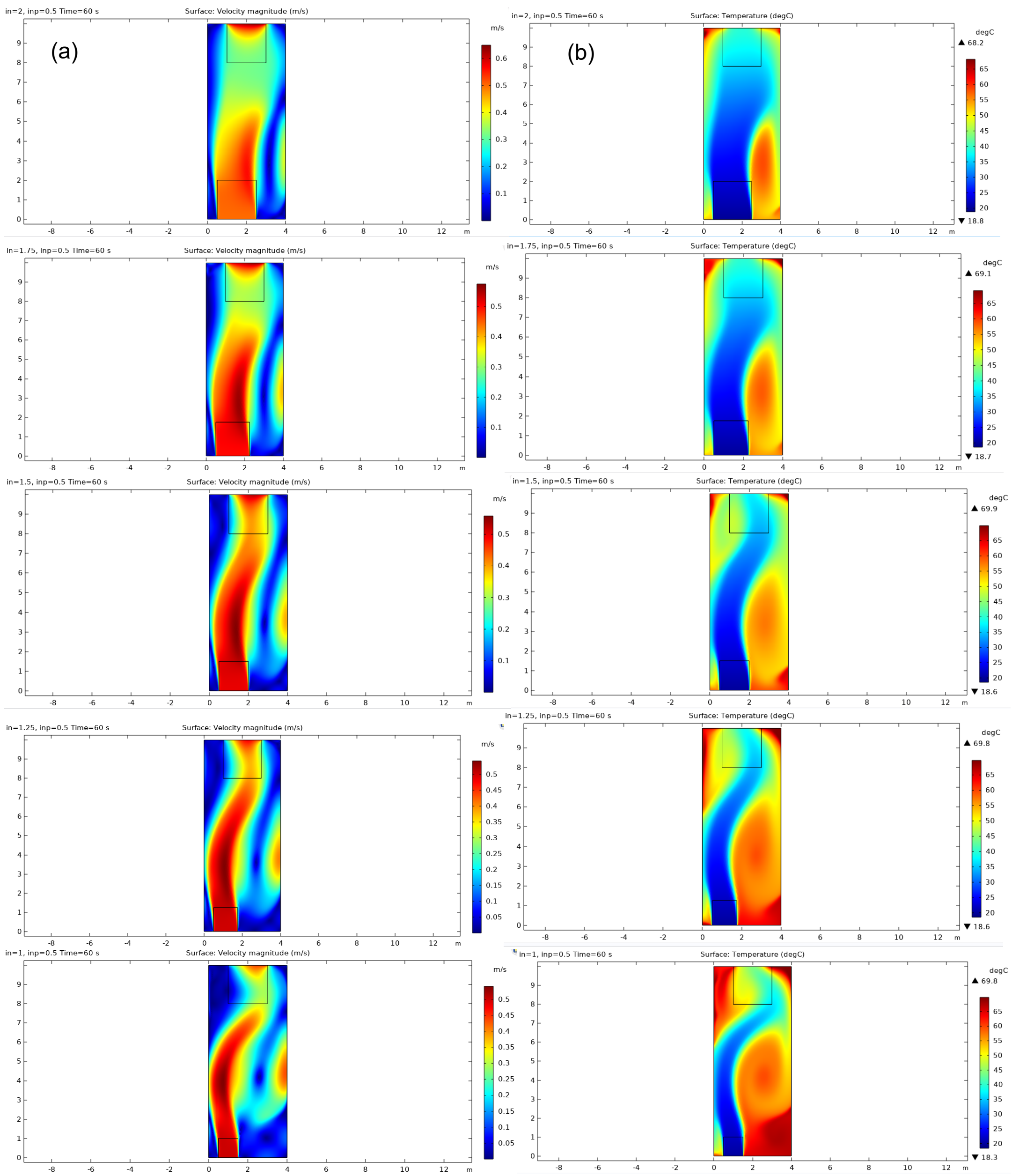


Figure 3: (a) Velocity and (b) Temperature spatial distribution at time 60 s (steady- state conditions) from inlet size of 2 m to 1.0 m at inlet location of 0.5 m

4. Conclusions

In conclusion, a strong correlation between the inlet size, inlet location and GHD process dynamics have been shown. COMSOL Multiphysics is the software package used to simulate the GHD. While the GHD model is 2D, this work has shown that structural parts of a GHD such as inlet impacts the process dynamics of drying. This

work provides the concept of modifying the inlet size of a GHD to dry a wide variety of crops, by using a single GHD, rather than multiple specific GHD each applicable only for a certain climate and crop. This work also illustrates the use of computational fluid dynamics software in designing GHD as it saves time, cost and aids in understanding dyer kinetics and performance.
There are recommendations for future work relevant to this work and field. Computational power is one of the key limitations for this work, therefore future work is recommended to model the GHD in 3D to be able to investigate the impact of inlet shape with other structural feature of GHD such as GHD size and roof shape on the GHD performance. This work models GHD in no-load conditions, therefore thermal modelling is not considered as no fruit/vegetable was modelled. Therefore, thermal modelling is recommended to be included in future models to calculate specific heat and mass transfer coefficients of specific dryer loads and to find the optimized location and size of an inlet for a particular agricultural product. Finally, to implement realistic environmental conditions in the GHD model such as solar sunshine hours, varying wind and rainfall by using data collected from weather stations to achieve a simulation that will provide insight of GHD performance in real-life without the expense and time of carrying out experimental work.

Nomenclature

p – Static pressure, Pa
C_p – Specific heat capacity, J kg^{-1} K^{-1}
S_T – Thermal sink source, W m^{-3}
λ – Latent heat of vaporization, J kg^{-1}
ρ – Density, kg m^{-3}
u – Velocity of fluid, m/s
T_f – Temperature of finite element, K
g – Body force per unit mass, m s^{-2}
t – Time, s

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