11th International Conference on Green Energy & Environmental Engineering (GEEE-2025)
Proceedings of Engineering & Technology – PET-Vol 94, pp. 288-295

Thermal Behavior of Grain Silos: Influence of Air Inlet Position on Cooling Efficiency

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***Abstract*— Modeling stored-grain has become an indispensable part of the grain sector to describe the theory of heat and mass transfer in cereals storage bin during ventilation with cooling air. Therefore, a careful monitoring of the grain mass parameters during this time is required. The main physical factors affecting grain storage are temperature and moisture content. Thus, higher temperature and moisture content increases respiration rate due to spoilage or mold growth and enzyme activity, and will affect the ability of stored grains to germinate. Cold temperatures will not damage stored cereals or pulses; hence, an aeration system is a convenient and economical means to solve those problems. Unlike the previous papers on this aspect, the present work developed a mathematical model to simulate distribution in temperature of wheat grain in a metal storage bin during ventilation with both ambient and refrigerated air. The model also explores the effects of different air inlet and outlet positions, utilizing the ANSYS Fluent software package, which is based on computational fluid dynamics (CFD). The results show that openings play a crucial role in the efficiency of grain cooling, as it directly influences airflow distribution and heat removal.**

***Keywords*— Ansys Fluent, Grain storage, Heat transfer, Temperature distribution,**

I. INTRODUCTION

Stacking cereals in metal silos is a frequently used method of post-harvest storage. However, in areas where the climate is hot or arid, this type of storage encounters significant thermal problems. Metal silos are highly sensitive to strong solar radiation and high air temperatures. These environmental conditions lead to significant heat exchange within the silo, both by radiation and natural convection [1,2]. This thermal accumulation, if it' is not controlled, leads to a gradual rise in the temperature of stored grains. Such overheating can have a range of detrimental effects, including the deterioration of nutritional quality, the mold formation, the proliferation of insects, and, in the most severe situations, the complete spoilage of the grains. This not only shortens their shelf life but can also render them entirely unfit for human consumption [3]. Therefore, controlling the thermal behavior of metal silos is crucial to maintaining both the quality and longevity of grain storage.

Furthermore, numerous researchers have turned their attention to the study and modeling of heat transfer in silos, taking into account the coupled phenomena of heat and mass. The aim of these methods is to gain a deeper understanding of the thermal behavior of grains during storage, and to develop optimized strategies that ensure a stable and efficient storage environment. For instance, food processing operations such as cooling, evaporation, and freezing can be optimized through grain engineering methods coupled with numerical simulations [4]. Within this context, several studies highlight aeration using ambient air as an efficient and economical technique to enhance cereal storage conditions [5–10]. Carrera-Rodríguez et al [11] proposed a multiphase mathematical model to

ISSN: 1737-9334

describe heat and mass transfer in an unventilated silo, and to study the influence of ambient temperature on grain storage in two dimensions. Their work showed that convection has a significant impact on temperature and humidity gradients. This method effectively removes excess heat and moisture. Moreover, Quemada et al examined the impact of various boundary conditions by simulating how ambient parameters influence the transfer of momentum, heat, and mass within silos [12]. Additionally, Barreto and Abalone [13] developed a 2D finite element model capable of predicting the temperature distribution, moisture migration, and natural convection currents in stored grain. They conclude that, for a given temperature gradient, moisture migration was more significant in soybean than in corn and wheat due to the hygroscopic properties and permeability of the grains. A mathematical model was developed by Hammami et al. (2016, 2017) [4] to simulate heat and moisture transfer in a ventilated silo equipped with a dehumidifier. The results showed that the temperature of the injected air plays a decisive role in the thermal and hygrometric evolution of the grain. While significant research has investigated the interaction between thermal radiation and natural turbulent convection [14, 15]. In particular, Casada [16] explored the effects of solar radiation on the upper air spaces of silos, but without accounting for the interaction between the air and the grain. Furthermore, other researchers have used three-dimensional models to analyze temperature variations inside a cylindrical steel silo, including and Zhang LeDao et al. (2016) [17]. Their work revealed that grains are strongly influenced by wall temperature, due to solar radiation and air thermal convection. All the study mentioned was limited only to analyzing the thermal behavior of grains without evaluating the impact of different air duct position that influences airflow distribution and heat removal.

In this context, our study proposes the development of a non-stationary mathematical model to simulate heat transfer within a grain storage steel silo by investigating the effect of various inlet/outlet configurations, using both ambient and refrigerated air. It enables us to predict the spatio-temporal evolution of temperature in the grain bed during storage, and to analyze in detail the influence of various ventilation parameters.

II. Material and Method

The model was applied to a 10m diameter, 10m high cylindrical metal silo filled with wheat. To assess the effect of the positioning of air inlet and outlet openings on cooling efficiency, three ventilation configurations were studied as shown in figure 1. In the first configuration, air is injected through an opening at the base of the silo and extracted through an outlet at the top. The second configuration features a lateral air inlet at 1m of height, with an outlet at the top. Finally, the third configuration also features a lateral air inlet at 1m, with two outlets placed symmetrically on the upper side walls of the silo. In all cases, the size of the inlet and outlet openings is set at 1 m.

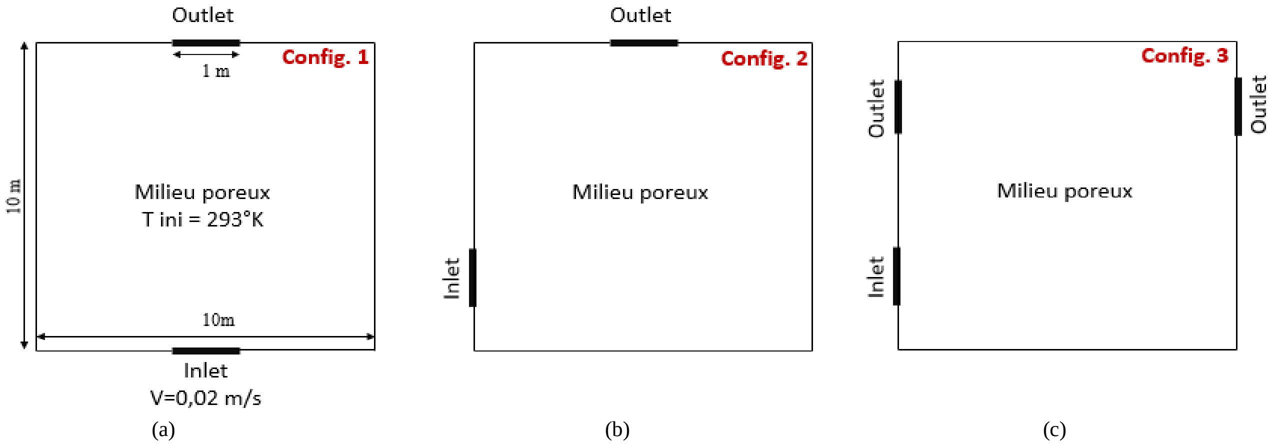

Fig. 1: Geometry of the bin silo with 3 configurations: (a) Bottom inlet and top outlet; (b) Side inlet and top outlet; (c) Side inlet and two opposite side outlets at the top

A. *Mathematical model*

The problem is solved using ANSYS Fluent software in transient mode, on a two-dimensional domain representing a vertical section of the silo. The mathematical model was developed to simulate and predict

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the thermal behavior of stored wheat during ventilation. Prior to establishing the governing equations, several simplifying assumptions were adopted to reflect the physical conditions of the system and to facilitate numerical resolution.

The main assumptions of the model are as follows:

- The porous medium (wheat bulk) is considered homogeneous and isotropic;
- The airflow is assumed to be incompressible;
- The effects of condensation or evaporation of moisture are neglected;
- No internal heat generation occurs within the silo wall material;
- Local thermal equilibrium is assumed between the grain and the surrounding air at all times (Ts=Tg);
- The biological respiration of the grains is considered negligible.

Based on these assumptions, the behavior of the system is governed by the fundamental conservation equations:

The heat transfer equation in the grain bulk:

$$\rho_S c_S \frac{\partial T}{\partial t} = \nabla . \lambda \nabla T \tag{1}$$

The heat transfer equation in the silo wall:

$$\rho_g c_g \frac{\partial T g}{\partial t} = \mathrm{k} \left(\frac{\partial^2 T_g}{\partial r^2} + \frac{1}{r} \frac{\partial T_g}{\partial_r} + \frac{\partial^2 T_g}{\partial z^2} \right) + q_{int} \tag{2}$$

Avec ρ_s and ρ_g are the bin wall material density and the grain density respectively in (kg\m^3); c_s and c_g is the bin wall and grain specific heat capacity respectively in (J\(kgK)); λ and k is the thermal conductivity of the bin wall and the grain in (W\(mK)); q_{int} is the internal produced heat in (W\m3); T and T_g are the temperature of the bin wall and the grain in (K).

These equations, coupled with appropriate initial and boundary conditions, allow the simulation of temperature evolution and distribution within the silo under various ventilation configurations.

B. *Initial and boundary conditions*

The typical limitations linked to storage heat transfer issues include ambient atmospheric conditions and solar radiation.

Initial condition associated to equation 1 is:

$$T(t=0) = T_0 = 293°K \tag{3}$$

Initial condition associated to equation 2 is:

$$Tw(t=0) = t_{w0} = 293°K \tag{4}$$

The boundary condition on the wall of the silo is given as:

$$-\lambda \frac{\partial T_g}{\partial_r} = h_{ext} \left(T_g - T_{ext}\right) - q_{ext} \tag{5}$$

III. RESULTS AND DISCUSSION

Before proceeding with the analysis of the different ventilation configurations, a mesh sensitivity test was carried out to ensure the accuracy and stability of the numerical results. Three element sizes were tested: 0.1 m, 0.05 m and 0.01 m. The criterion for selecting the optimum mesh size was based on a comparison of the average temperature profiles in the silo, in particular their temporal evolution. As shown in Figure 2, the curve corresponding to the M2

ISSN: 1737-9334

= 0.01 m mesh deviates significantly from the other two, indicating a finer resolution of thermal gradients. On the other hand, the curves obtained for the 0.1 m and 0.05 m mesh sizes are very close, suggesting a relative stability of results between these two sizes. However, the 0.1 m mesh size was selected as the best compromise, as it ensures good accuracy while considerably reducing computation time compared with the finest 0.05 m mesh size.

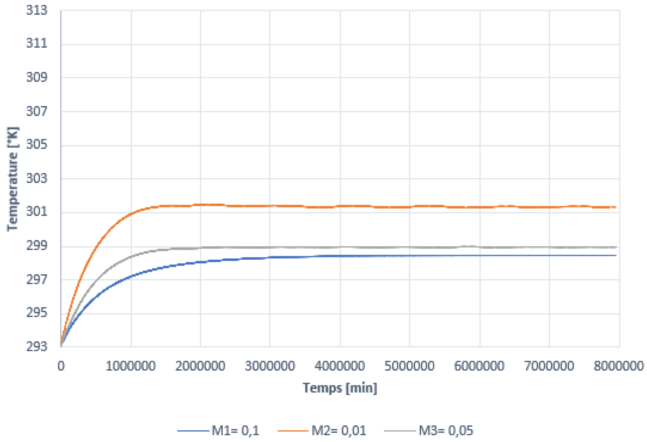
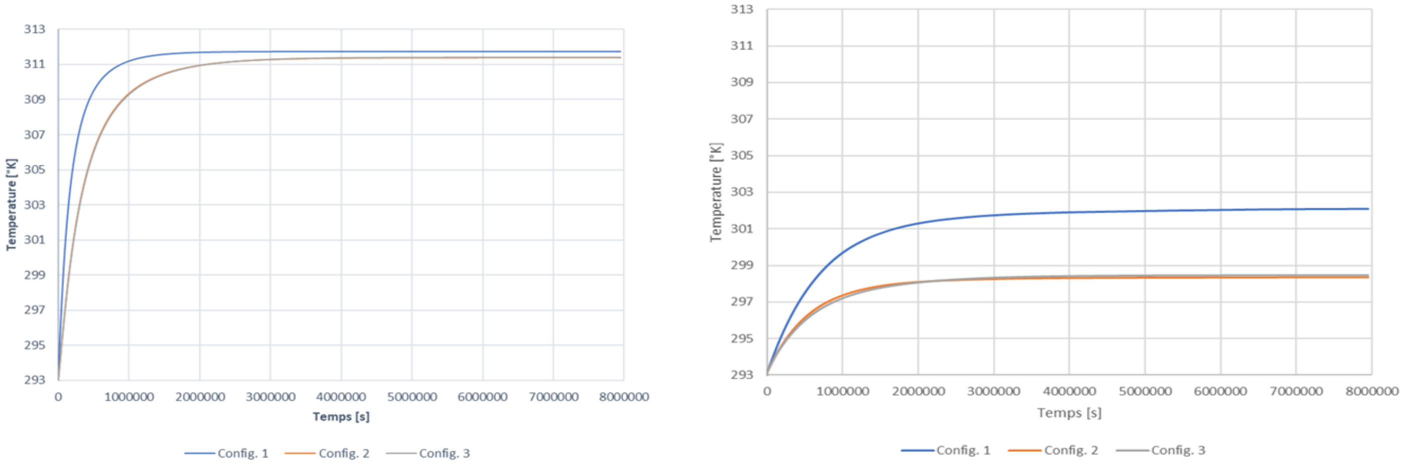


Fig.2: Temperature curve over time for different mesh sizes (3 months): M1= 0.1 m; M2= 0.01 m and M3= 0.05 m

Figure 3.a shows the evolution of the average temperature in the silo over a three-month period, for the three ventilation configurations using ambient air. It can be seen that, in all three cases, the average temperature rises progressively over time, until stabilizing at around 312 K, the temperature of the injected ambient air. This rise in temperature is mainly due to the effect of global warming, which increases the thermal load on the metal walls of the silo through solar radiation and natural convection. This accumulation of heat in the grain mass is an unfavorable factor for storage, as it accelerates deterioration phenomena: mold development, insect proliferation and loss of nutritional quality. Under these conditions, the cooling objective is not achieved, since the temperature of the grains remains too high to guarantee optimal preservation. For this reason, cold air ventilation was studied, to limit internal overheating and sustainably lower the temperature of the stored grain.

As shown in Figure 3.b, cold air injection maintains the average temperature in the silo at a much lower level, with a slight rise compared to the initial temperature (around 298 K), but without ever reaching the critical levels observed when ventilating with ambient air. This shows that the cold air not only compensates for the effect of external heating, but also creates a thermal dynamic favorable to grain preservation. The use of refrigerated ventilation therefore represents a promising solution for extending shelf life, reducing losses and guaranteeing the quality of stored products.



(a) (b)

Fig. 3: Average grain temperature curve over time for different configurations (3 months):
a: Ventilation with ambient air; b: Ventilation with colling air

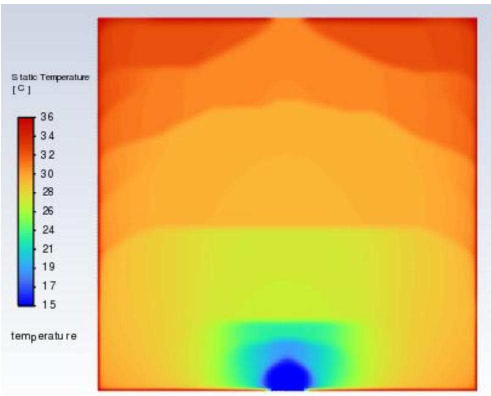
ISSN: 1737-9334

Figures 4.a, 4.b and 4.c illustrate the temperature contours obtained for the three ventilation configurations, after cold air has been injected into the silo. In configuration 1 (figure 4.a), cold air enters at the base of the silo, generating a vertical upward propagation. Blue zones (between 15 and 19°C) indicate effective cooling around the inlet, but this remains confined to the lower zones. The upper parts of the silo, on the other hand, retain high temperatures, due to insufficient air mixing in this region and increased exposure to solar radiation at roof and wall level. This limits the efficiency of overall cooling and creates vertical thermal gradients unfavorable to good storage.

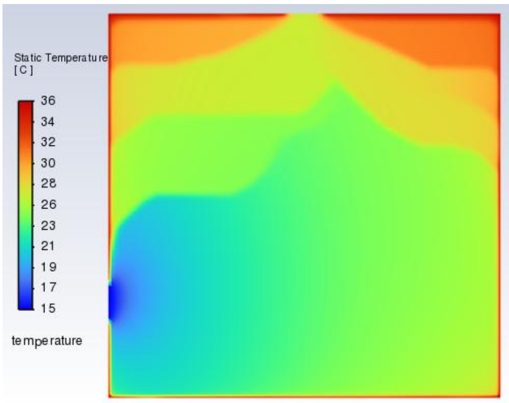
Figure 4.b (config.2), with an inlet positioned laterally and an outlet at the top, shows a more uniform and better-directed propagation of cold air. The temperature contours reveal a more even distribution of cold throughout the silo volume, reaching both upper and lower layers. This good distribution is due to a transverse sweep of the air flow, which enables better penetration of the cold and more efficient renewal of the warm air. As a result, this configuration succeeds in lowering stock temperatures more evenly, while limiting localized overheating zones. Despite slightly higher wall temperatures, probably due to heat exchange with the outside environment, the silo core is better controlled overall (26°C).

On the other hand, configuration 3 (figure 4.c), despite having two side outlets at the top, shows significant heat accumulation in the central upper section. This arrangement limits the natural ascent of cold air to the top of the silo, preventing a complete vertical. This can lead to condensation at the top of the silo. sweep which is unfavorable for long-term grain preservation.

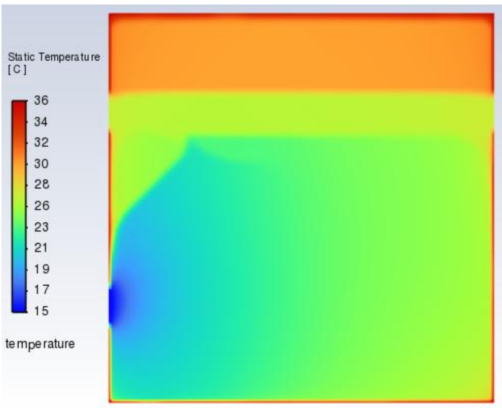
In conclusion, configuration 2 proved to be the most efficient of the three studied. It provides better thermal coverage of the silo, a significant reduction in hot zones, and promotes more efficient ventilation, both in terms of air distribution and temperature homogeneity. This choice is therefore justified by its ability to maintain grains at a more stable, lower temperature, an essential condition for limiting spoilage, fungal development and quality losses during storage.



(4.a)



(4.b)



(4.c)

Fig. 4: Temperature contour for: 4.a: configuration, 4.b: configuration 2 et 4.c: configuration 3

ISSN: 1737-9334

Figures 5.a and 5.b show the temperature evolution as a function of time (t) and horizontal position (x) for different silo heights (y =1m, 5m and 9m), in the case of configuration 2. These curves are used to evaluate cooling efficiency at different vertical levels. Cooling is particularly effective in the low layers (y = 1 m), where temperature drops rapidly due to the direct proximity of the lateral inlet. At mid-height (y = 5 m), the effect of cold air is still noticeable, although more attenuated, which reflects a moderate cooling efficiency. On the other hand, at a height of 9 m, corresponding to the upper layers of the silo, the decrease in temperature is slower and less marked.

This vertical distribution shows a relatively uniform horizontal spread of cold air at the base, but a gradual loss of efficiency with height. This limitation is probably due to the thermal inertia of the grain, the natural stratification of the air as well as heat exchange by radiation and convection with the external environment at the walls and roof. As a result, cold air is not able to reach the top of the silo effectively, which compromises complete thermal homogeneity. These results confirm the need to optimize vertical air circulation in order to improve cooling performance throughout the storage volume.

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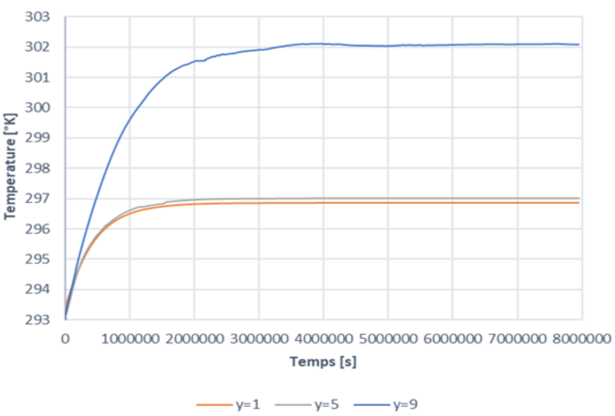
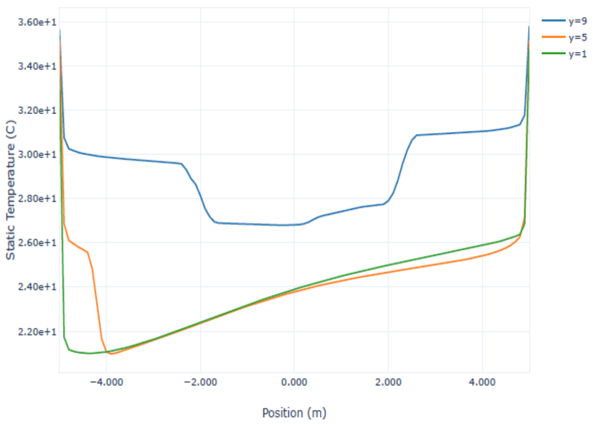


(5.a)



(5.b)

Fig. 5: Temperature curve for different positions (y=1, 5, 9 m): 5.a: as a function of time, 5.b: as a function of x

IV. Conclusion

This study allowed the development of a general model for simulating heat transfers in a grain silo. The result is that cold air ventilation is essential, as ambient air at 40°C is not suitable for cooling. The position of the openings, especially the inlet, plays a key role in maintaining grain quality. In addition, a lateral cooling configuration allows for better distribution of cold air, ensuring thermal uniformity that is more favorable to grain conservation.

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ISSN: 1737-9334