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Geleneksel Tahıl Kurutuculardaki Kanal Geometrisinin Kurutma Havası Akışına Etkisinin Gözenekli Ortam Yaklaşımıyla İncelenmesi

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Öz: Pek çok tarım ürünün kurutulduktan sonra depolanması geleneksel bir uygulamadır ve bu şekilde yıl boyu kullanılması sağlanır. Hasadı yapılan tahılın depolama ömrünün artırılması için nem içeriğinin kabul edilebilir seviyelere (genellikle <%15) indirilmesi gerekir. Yığın kurutma prosesinde karışan karşıt akışlı havayla kurutma, en yaygın ve geleneksel yöntemlerden biridir. Bu uygulamada, kurutucu yatağına yerleştirilen hava kanalları sayesinde üretilen hava akışı, tahılların içerisinden tahıl akışına ters yönde akmaya zorlanır. Tahılların içerdiği nem zorlanmış taşınım yoluyla kurutucudan dışarıya atılır. Ancak, kurutuculara yerleştirilen hava kanallarının hem tahıl akışını engellememesi hem de mümkün olan en iyi kurutma performansını sağlaması beklenir. Bu çalışmada, karşıt akışlı bir tahıl kurutucu için hesaplamalı akışkanlar dinamiği (HAD) modellemesi yapıldı ve kurutma kanalları geometrisinin prosese etkisi incelendi. Kurutucu içerisindeki 2-boyutlu akış modellemesi için Fluent 2020 R2 ticari yazılımı kullanıldı. Gözenekli ortam olarak modellenen tahıl bölgesindeki hava akışı, kurutucu hava kanallarının üç farklı geometrisi (dairesel, açısal ve düz) için hesaplamaya dâhil edildi. Tahıla karışmayan kurutma havasının havanın dolaştığı hava kanalları için sabit sıcaklık sınır koşulu (37 °C) uygulandı. Analiz sonucunda, farklı hava akış hızlarının kurutma prosesindeki davranışını belirlemek için 5 farklı giriş hızının (0,005-0,25 arası) kurutucu çıkış sıcaklığı ve akış boyunca fark basınç değişimi hesaplandı. Giriş hızındaki artış, tüm modeller için basınç farkını ve buna bağlı olarak akışın kararlılığını artırdı. Çıkış sıcaklığı ise hızın 5 kat artmasıyla yaklaşık 2,5 °C düşüşe sebep oldu. Elde edilen sonuçlar, nem atma için yeterli çıkış havasının gözenekli ortamın yapısına ve akış geometrisine bağlı olduğunu gösterdi. Bu analiz için en iyi akışın dairesel kesitli model için olduğu ve çıkış sıcaklığının kabul edilebilir seviyelerde olabileceğini ortaya koydu.

Anahtar kelimeler: Tahıl kurutucu, kurutma, basınç düşüşü, gözenekli ortam.

Investigation of the Effect of Duct Geometry on Drying Air Flow in Conventional Grain Dryers by Porous Media Approach

Abstract: It is a traditional practice to store many agricultural products after drying, ensuring that they are used all year round. Mixed counter flow air drying is one of the most common and traditional methods in the bulk drying process. In this application, the air flow produced by the air channels placed in the dryer bed is forced to flow through the grains in the opposite direction to the grain flow. The moisture contained in the grains is thrown out of the dryer through forced convection. However, it is expected that the air ducts installed in the dryers should not obstruct the flow of grain and provide the best possible drying performance. In this study, computational fluid dynamics (CFD) modeling for a counter-flow grain dryer was performed and the effect of the geometry of the drying channels on the process was investigated. Fluent 2020 R2 commercial software was used for 2-D flow modeling through the dryer. The airflow in the grain zone, modeled as porous media, was included in the calculation for three different geometries of the dryer air ducts (circular, angular, and straight). A constant temperature boundary condition ($37°C$) was applied for the air ducts in which the drying air circulated without mixing with the grain. As an output of the analysis, the dryer outlet temperature and differential pressure variation along the flow were calculated for 5 different inlet velocities (between 0.005-0.25) to determine the behavior of different air flow rates in the drying process. The increase in the inlet velocity increased the pressure difference and consequently the stability of the flow for all models. The outlet temperature decreased by about 2.5 °C with a 5-fold increase in velocity. The results showed that the sufficient outlet air for moisture removal depends on the structure of the porous medium and the flow geometry. For this analysis, the best flow was found to be for the circular cross-section model and the outlet temperature could be at acceptable levels.

Key words: Grain dryer, drying, pressure drop, porous media.

1. Introduction

Millions of people worldwide rely on grain for energy, vitamins, and minerals in their daily diet [1]. The quality of grains can be affected by various factors such as variety, climate, pre-harvest treatments, and technical management. However, post-harvest handling is also crucial to ensure long-term preservation and availability of

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the product [2]. To maintain grain quality, it is important to avoid physical damage, changes in chemical compositions, and contamination by insects or fungi during post-harvest operations such as drying, storage, and processing [3]. The choice of procedures adopted in these operations can greatly influence grain quality [4-5]. Therefore, it is essential to use modern technologies and appropriate equipment to ensure quality and minimize physical and chemical damage to grains.

When harvesting grain products, the moisture content must be reduced for long-term storage. This is done through dehumidification at appropriate temperatures and airflow rates according to the specific product. Sun drying can be unreliable and lead to contamination and uneven drying, so devices like counter-flow grain dryers are often used. These dryers work by loading moist grains at the top and allowing them to flow down while hot air is simultaneously forced upward through the dryer, removing moisture from the grains. The rate of filling, bulk density, porosity, and permeability all affect the drying process. Drying air temperature is a crucial factor that affects the quality of grain. The use of heated air is an obvious way to dry grains. Heated air has a high vaporization capacity and its enthalpy is increased. Evaporation and internal pressure in grains increase in the presence of additional heating [6-7]. The main advantages of heated air drying are the high drying capacity and shorter drying time, while the disadvantages are the energy cost to heat the air and the damage to the grains due to the increase in temperature [8]. When this temperature is too high or low during the grain-filling stage, it significantly deteriorates the quality of the grain for consumption. This can result in lower yield of processed grain, changes in color and viscosity profile, and altered functional properties, such as gelatinization temperature [9]. Proper grain harvest plays a significant role in maintaining post-harvest grain quality. For larger grains, the ideal harvest water content range is between 19% and 22%, while for medium-sized grains, it is between 22% and 24% [10]. Harvesting grains with low water content results in reduced yields and often leads to cereal grain cracks and breakage due to moisture absorption during milling. To facilitate the logistics and flow of the grain mass during post-harvest stages, especially during receiving and drying operations, it is recommended to harvest grains with a water content between 18% and 23%. Additionally, Lang et al. [11] found that delaying the drying of grains at 25°C leads to phenolic compounds' greater degradation and reduced protein solubility.

Many studies have explored the effective parameters in drying various agricultural products, such as corn and Roman chamomile. It has been found that pressure drop and resistance to flow velocity increase with decreasing moisture content and air temperature [12]. To design an optimal grain dryer for any type of grain, it is important to have knowledge of the grain's physical and thermal properties, including heat and mass transfer, moisture diffusion, activation energy, and energy consumption. During the drying process, heat and mass are transferred between the grains and the drying air [13-14]. For effective drying, the water vapor pressure of the grains must be greater than that of the drying air. If the water vapor pressure of the grains is low, the product will be damp, and if the pressures are the same, a hygroscopic equilibrium will occur between the product and the environment it will be stored in. However, reducing the water content of cereals leads to chemical and physical changes in the product. When water is lost, the grain size decreases due to external pressure, while heating causes the internal pressure to increase. This process exposes the grain to high mechanical stresses that can cause cracks, fissures, and fractures because the grain surface lacks the plasticity or elasticity to support them. Mathematical models are used in drying analysis, as well as in the development and optimization of dryers to describe such phenomena [15-16]. For example, Nowak and Przystupa [17] presented an algorithm for the assessment of the efficiency of grain dryers by calculating energy rating indices including water vapor content, temperature, and dryer capacity.

Some studies suggest the use of additional systems to make the drying process more economical and operative. Scaar et al. [18] used a numerical model based on Computational Fluid Dynamics (CFD) to study the airflow distribution in a mixed-flow dryer and the effect of different bed materials and air duct arrangements. The study found that a horizontal air duct arrangement with one inlet and two diagonal outlets was more effective than one inlet and four outlets, which reduced dryer performance by half [19]. Cao et al. [20] conducted a study to investigate the shape, size, and arrangement of air ducts and their influence on drying characteristics in a mixed-flow grain dryer. For this purpose, they modeled a 60cmx170cm drying duct zone and simulated the effect of duct layout and flow parameters with a computer program. They concluded that increasing the number of ducts increases the dryer capacity and increasing the air flow rate increases the drying effect. As a result, they proposed a small and compact duct layout in dryer ducts. In a CFD simulation study to demonstrate the design effects of air ducts in the dryer [21], air flow distributions were shown and the necessity of designing new dryers was emphasized. In another simulation study of a double bed mixed flow dryer [22], the flow direction of the air in the dryer was altered to spend more time in the grain bed. The modeling changes emphasized the importance of intrinsic permeability, which is the ability of air to pass through the porous medium and has a direct effect on the flow. This parameter depends only on the type of stack and provides accurate results for investigation. Although new drying techniques and alternative dryers have been developed, these proposed improvements for conventional dryers are still unsatisfactory.

Researchers in particle flow field have shown interest in studying fluid flow through packed bad with particle size using the porous media approach [23-24] which can be adapted to the grain dryers. However, the mathematical modeling of deep bed drying processes, such as mixed flow dryers, is a more extensive topic where grain flow and air flow interact in different ways to exchange heat and mass. The effect of different shapes of flows on the grain and air flows through a mixed flow dryer has already been studied by Klinger [25]. This study focuses on the effects of drying duct shape and pattern on grain dryer.

Numerous dryer designs have been examined in various studies, depending on the type of cereal product that requires storage. However, researchers are continuously seeking to develop the most effective conventional dryer for grain types with differing characteristics in terms of size and shape. In particular, it seems that studies on the shape and layout of the heating air ducts in conventional grain dryers have been insufficient and it is worthy of further study. This study aims to investigate the size and shape factors using a porous media approach and to determine the impact of drying air ducts on average porous media. ANSYS Fluent software was used to model drying ducts in porous media. The duct walls were assumed to have a constant temperature boundary condition, with energy supplied from an external source. The pressure drop across the dryer and other flow parameters related to three different duct sub-geometries allowing the grain to flow were simulated.

2. Application and Method

2.1. Geometry and modeling

The location of drain dryers is usually at a pressure of 1 atm and at the standard ambient temperature. The flow conditions depend on the grain loading condition and the characteristics of the supplied air. In traditional air dryers, the grain is loaded from the top and flows downwards under its own weight, while the drying air is forced to flow upwards by a fan located at the bottom. The air ducts, which direct both flows and contribute to the drying process, are situated under specific ambient air boundary conditions. This is depicted schematically in Figure 1.

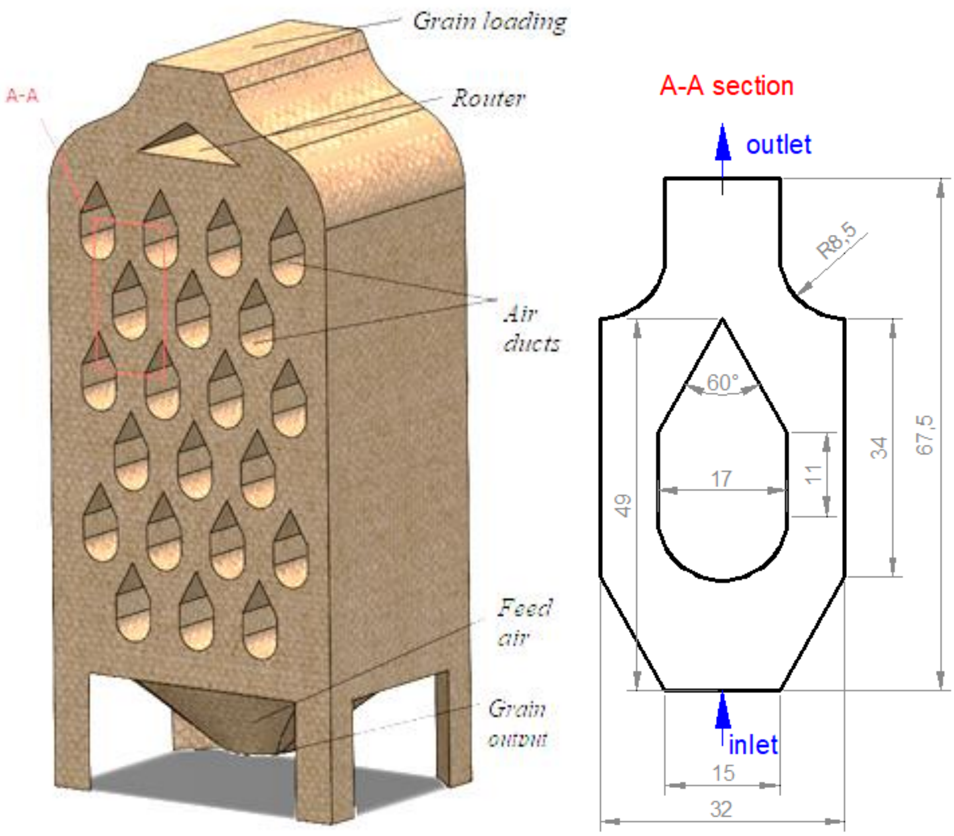

Figure 1. Grain dryer schematic and basic drying process with A-A section (cm)

The dimensions of the designed drying channel pattern can be read from this figure. The overall dimensions of the dryer vary according to the loading capacity and their effects on the sectional analysis are not taken into account. Plates at the top and bottom of the dryer guide both grain and air flow into the ducts, ensuring similar flow conditions for each channel. To improve the air conditions in a grain pile, it is possible to adjust the permeability conditions for different types of grain. A-A cross-section is used to represent the flow and drying process inside the dryer. The air enters through a 15 cm wide lower inlet and flows upwards along the drying duct, expanding to a width of 32 cm. Across the flow in the cross-section, the grain particles, and the feed air travel in opposite directions, contacting the heater channel walls. The outlet cross-section has the same width as the inlet. In this type of flow modeling, the permeability can differ in the horizontal and vertical directions. Often, the permeability in the horizontal direction is higher than in the vertical direction, making the medium non-isotropic [26-29].

For this study, we created a model that takes into account the flow around air ducts that do not move. We established a symmetry condition for the side walls. The air ducts were kept at a constant temperature of 37 ºC which represents the traditional low speed drying temperature [30]. We analyzed three different duct and flow geometries (circular, angular, and straight edge) while maintaining the dimensional ratios. Figure 2 shows the 2D modeling of the specified duct arrangements.

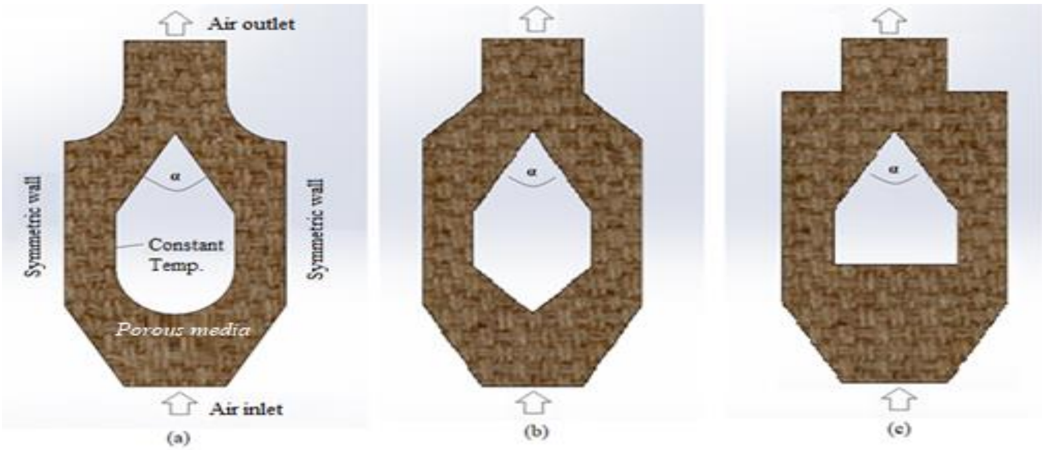

Figure 2. Channel modeling along the flow field a) Circular b) Angular c) Straight

2.2. Governing equations for air flow

Drying air flow is assumed to be in continuous medium and incompressible flow conditions. For the energy equations, flow conditions at constant temperature are considered. In this case, the continuity equation can be written as in Equation 1.

$$\nabla . u = 0 \tag{1}$$

Here $u = [u, v]$ represents the velocity vector for two-dimensional flow. The basic model for fluid flow in porous media is described by Darcy's law. Ignoring the effect of gravity, the velocity is defined by Equation 2 [24].

$$u = \frac{1}{\mu} K \nabla p \tag{2}$$

Here $\nabla p \ (= \Delta p / L)$ is the pressure gradient of flow through a porous media and K is the permeability coefficient of the porous medium. Permeability is a measurement of the ability of fluids to flow through a multiphase material. It is therefore an important evaluation parameter for flow analysis. In typical grain dryers, the pressure difference for drying air is usually less than 1 kPa. Darcy's law was developed for slow flows and does not fully satisfy the relatively fast flow conditions in dryers. Therefore, the pressure gradient needs to be rewritten to account for high-speed inertial forces. This relationship was presented with the *Blake–Kozeny* and the *Burke–*

Plummer equations and the pressure gradient was redefined by the expression of Ergun (1952) [27] as in Equation 3 [28].

$$\frac{\Delta p}{L} = 150\frac{\mu\,(1-\varepsilon)^2}{d^2\varepsilon^3}u_m + 1.75\frac{\rho(1-\varepsilon)}{d\,\varepsilon^3}u_m^2 \qquad (3)$$

Where Δp is the pressure drop across the cross section, μ and ρ are the dynamic viscosity and density of the fluid, respectively, and u_m represents the mean velocity in the flow cross section. d and L are the inlet cross-section length and flow length, respectively, related to the flow geometry. ε in the equation is the porosity expression that enables the porous media approach according to grain type.

The heat transferred along the flow is the heat carried by the drying air and is given as in Equation 4. The outlet temperature is directly related to this expression.

$$\dot{Q} = \dot{m}C_{air}(T_{in} - T_{out}) \qquad (4)$$

In this equation, $\dot{m}$ is the mass flow rate, C_{air} is the specific heat of the flow air. And T_{in} and T_{out} represent the inlet and outlet temperatures respectively. The properties of the air used for the flow are given in Table 1.

Table 1. The Properties of the Fluid

Fluid	Temperature [^{o}C]	Density [kg/m^3]	Dynamic viscosity [Pa.s]	Specific heat [J/kgK]	Thermal Conductivity [W/mK]
Air	*27*	*1.225*	*1.7948x10^{-5}*	*1006.43*	*0.0242*

2.3. Mesh independence test

In finite element analysis, it is important to prove the independence of the results from the number of cells or nodes. To reduce the impact of the number of elements on the results, we aimed to minimize its dependence by practicing trials of an increase in the number of cells for circular model. We modeled a flow field and conducted four finite element applications with increasing cell numbers. These were 18575, 77364, 125833, and 175422 total cell numbers, with a focus on the denser mesh near the solid edges. The outlet temperature results obtained according to the increase in the number of cellular elements are 31.28, 32.17, 32.48 and 32.482 Pa, respectively. The distribution of cell division can be seen in Figure 3.

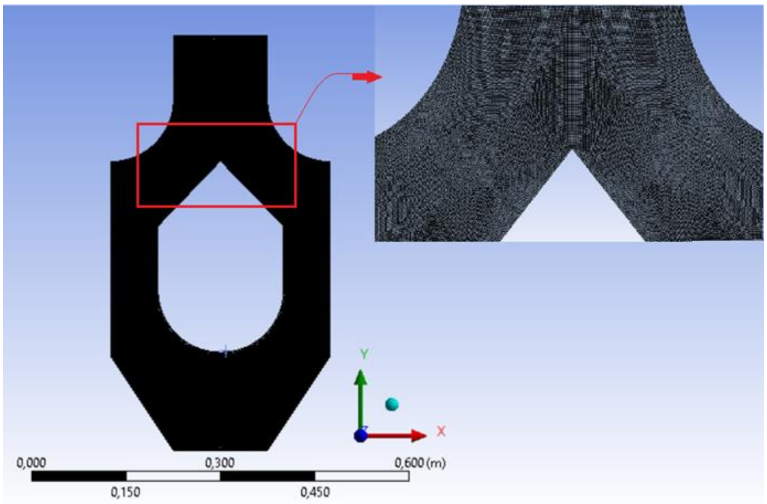

Figure 3. Finite element model

The results for the pressure drop remained nearly stable after the third cellular analysis, as shown in Figure 4. To prevent lengthy analysis times and issues with computer memory, subsequent calculations were performed using a cell number of 125833.

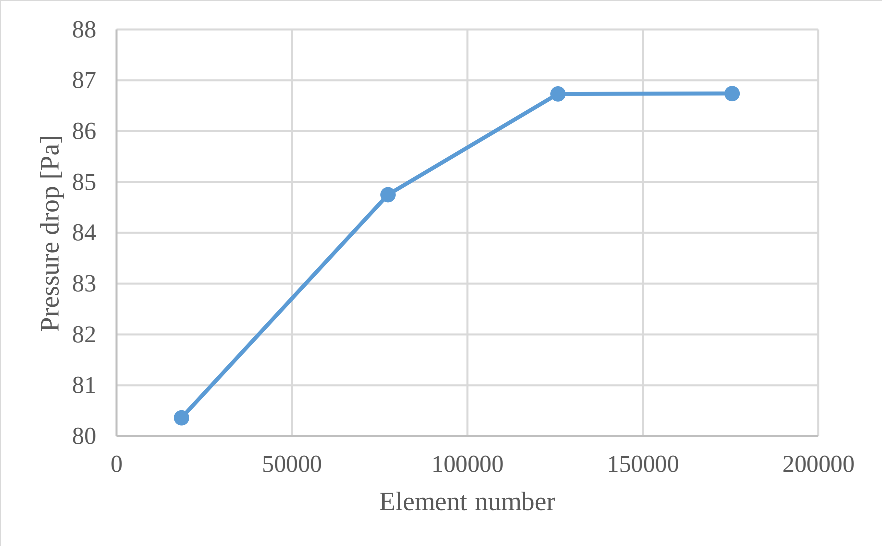

Figure 4. Change of dependency on cell number

3. Results and Evaluation

3.1. Simulation settings

The system consists of a continuous medium in both horizontal and vertical directions. Air enters at the bottom of the model with an inlet velocity and leaves from the top by flowing over the surface of the ventilation ducts. The temperature is kept constant at 37 ºC as required by the assumption of the constant surface temperature boundary condition. The convergence criterion for velocity and momentum conservation is 10^{-5}. But, for energy conservation, it is 10^{-6}. The continuity equation error is 10^{-9}. The porous medium is defined as wood, the air ducts as steel, and the fluid as air. The y-direction permeability is three-quarters of the x-direction permeability. It is clear that in the case of grain loading, the permeability effect will decrease in the gravity direction due to the bulk effect. In other words, the flow capability of the drying air in the y-direction is slightly less than in the x-direction. This effect varies according to the grain density. This was considered as an average effect. Permeability was left as default in these conditions for analysis according to the wood grain bulk. And the value of porosity was selected as 0.1 as an average value which it is allowable value for a grain bulk [29]. The simulation is run five times, with normal inlet air velocities ranging from 0.05 m/s to 0.25 m/s in all three modes. The spatial discretization is quadratic for all parameters, and the pressure-velocity related solution method is chosen as Couple. The initial convergence is taken as Hybrid. The study is conducted on a computer with 32 GB RAM and a 10-core i7 processor, and each run takes about 3 hours.

3.2. Validation of the model and solution

The study compared the results of its porous media modeling with that of Timo Oksanen [22], which had a similar approach. Figure 5 illustrates this comparison, displaying the relationship between inlet velocity and pressure drop. It was found that the outcomes for inlet conditioning at low Re numbers were similar and consistent with one another. Similarly, the increase in pressure drop with increasing volumetric flow rate of drying air in a conventional grain dryer was demonstrated in the study of Misr et al [30]. It is confirmed from that study that this increasing trend does not change for different humidity and temperature conditions.

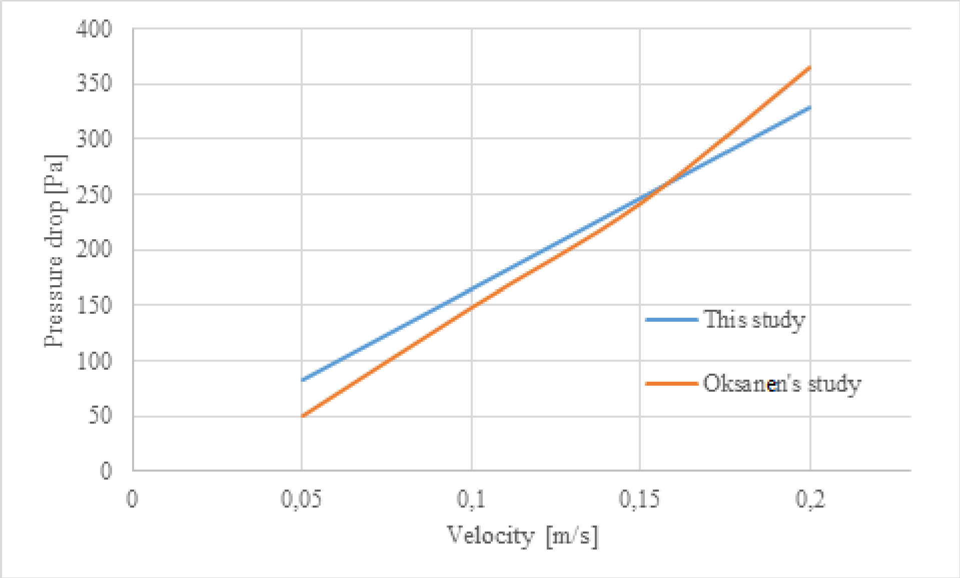

Figure 5. Validation of the analysis

3.3. Flow parameters in nonporous media

Flow analysis in non-porous media involves the study of the variation of standard air flow through geometric obstacles. It is used to determine the extent of heat transfer from air to surfaces or from surfaces to air. In this study, firstly, the models with only air flow were analyzed to determine the behavior of velocity, temperature and pressure variations in the medium. To analyze the behavior of the air flow in the modeled geometries, an analysis was conducted on a non-porous medium with the same initial and boundary conditions as the proposed system. The resulting velocity, pressure, and temperature contours can be seen in Figure 6. The fluid flow is uniformly directed from the surfaces of the channel towards the outlet. As expected, the maximum pressure drop occurs in the outlet region. The constant temperature channels exert a drying effect on the flow throughout the defined zone. As expected, in all three models, high velocity and low pressure combinations occur in the narrowed channels. The obtained maximum velocity value of 0.0627 m/s is considerably higher than that of the porous medium. Similarly, it is seen that low pressure conditions are formed.

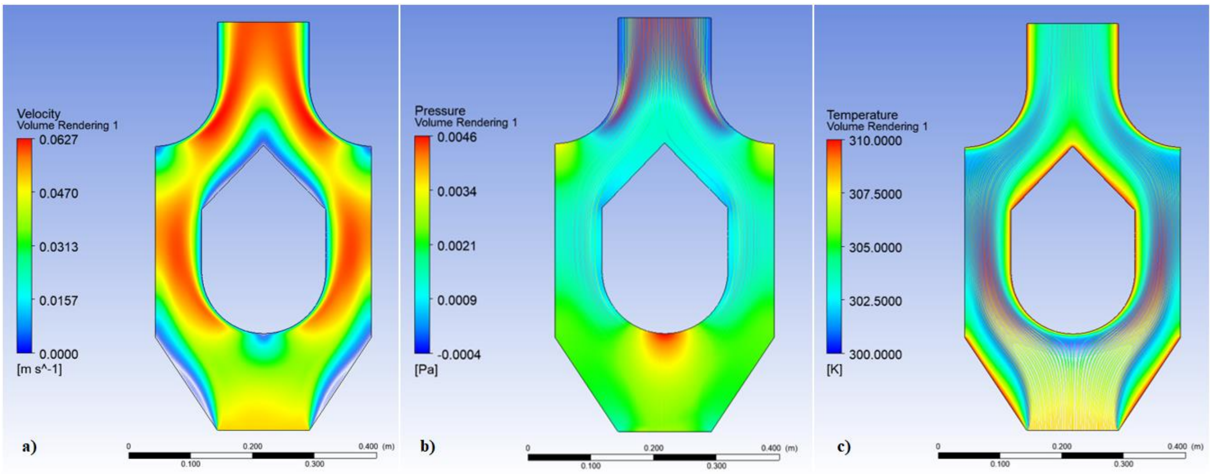

Figure 6. Flow contours in a hollow flow region a) Velocity b) Pressure c) Temperature

3.4. Flow parameters in porous media

3.4.1. Velocity contours

The results of modeling three different models with a normal inlet velocity of 0.01 m/s are shown in Figure 7. It is crucial that the airflow during the drying process moves in a continuous and controlled upward direction. The straight-sided duct model showed irregular pressure distribution, hindering the flow. While the angular model partially ensured flow continuity, the circular edge model exhibited the highest exit velocity and uniform velocity distribution. In all three models, although much lower velocity gradients than in the non-porous medium were observed, it was found that flow was almost non-existent in the straight model. In the proposed circular model, the corner areas, which can be called dead volume, are significantly eliminated.

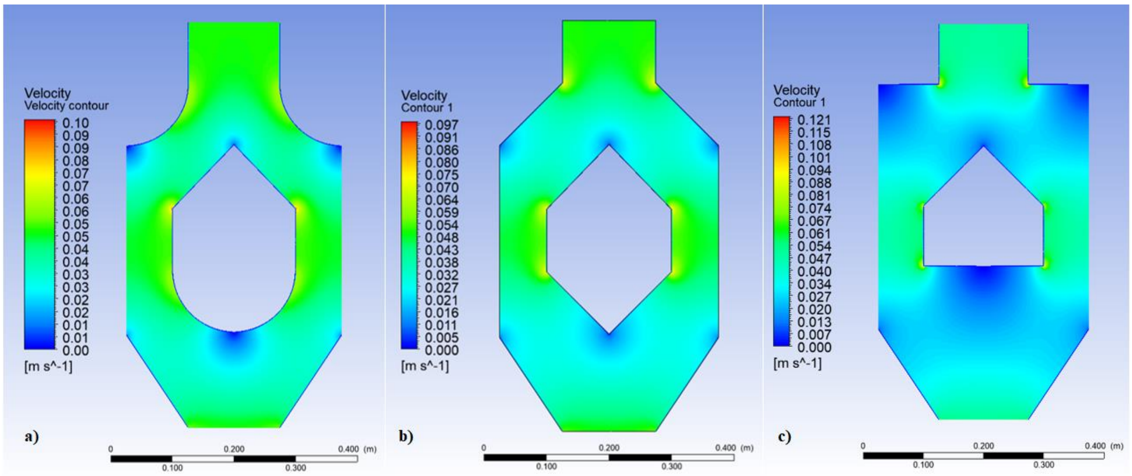

Figure 7. Velocity contours a) Circular b) Angular c) Straight

3.4.2. Pressure contours

In most channel flow models, the velocity distribution often also gives insight about pressure variations. However, for this study involving porous media, it is useful to see this tendency. As seen in Figure 8, the pressure contours and their relationship with the surface geometries remain consistent for all three models under the same initial and boundary conditions. However, it is important to note that the straight model has the lowest pressure gradients. It is anticipated that the fluid's entry will lead to a high-pressure region, and this is true for all three models. However, it is evident that the circular edge model provides the most uniform pressure distribution for the flow. This trend aligns with the findings of Scaar's study [31] reported in the literature.

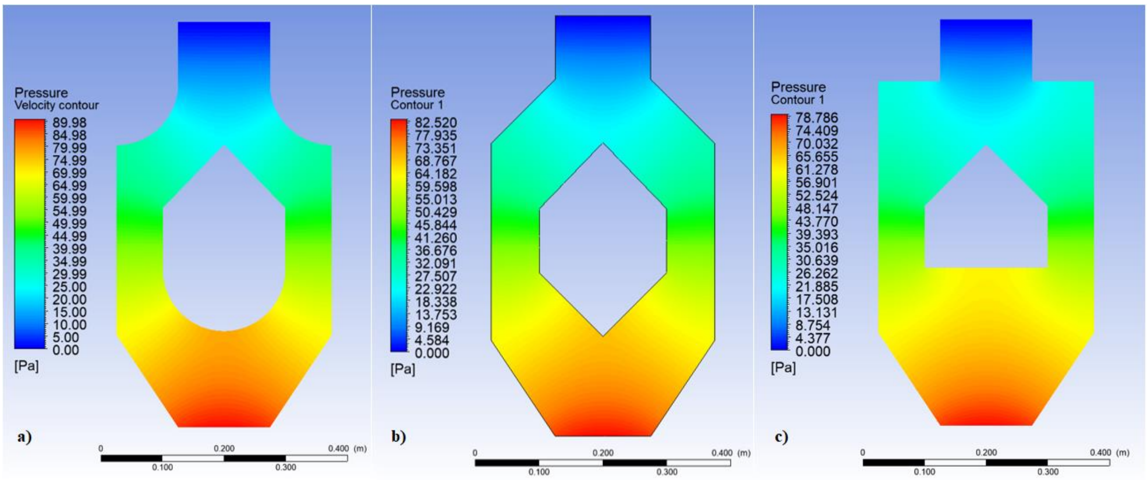

Figure 8. Pressure contours a) Circular b) Angular c) Straight

3.4.3. Temperature contours

The purpose of including pressure and temperature contours in the analysis is to achieve the desired airflow. In this way, it can be possible to ensure steady conditioning across the cross-section. However, the temperature distribution in the flow zone is also crucial for effective drying. The ducts with constant temperature conditions gradually dry the grains and heat the flowing air throughout the entire flow zone. Figure 9 displays the temperature contours for all three models at the same flow rate. The circular edge model exhibited the earliest heating along the duct, compared to the straight and angular edge models.

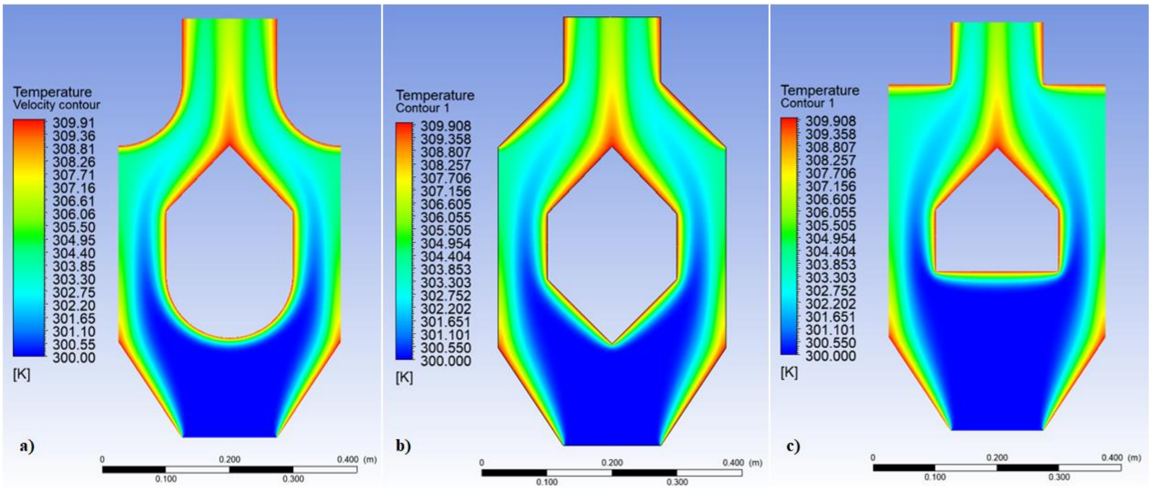

Figure 9. Temperature contours a) Circular b) Angular c) Straight

3.5. Comparison of the effects of flow field models

For the flow geometry, the pressure drops show the difference between the inlet and outlet pressures. However, it should be noted that the boundary conditions for the flow problem in the channel geometry are defined as velocity inlet and pressure outlet. Therefore, the pressure value calculated at the outlet of the modeled geometry gives the pressure drop across the flow. This information can tell us how well the drying air flows. If the pressure drop increases, it means less pumping power is needed. On the other hand, if the pressure drops are close to zero or negative, it negatively affects the flow's condition, making it inconsistent. By increasing the velocity of the inlet drying air, the flow through the porous media is expected to be faster. Figure 10 shows the pressure drops and outlet air temperature for all the models. This was observed for all three models. In the circular model, the total pressure drop across the drying section is the highest for all flow rates. This means that systematically higher outlet temperature values will result.

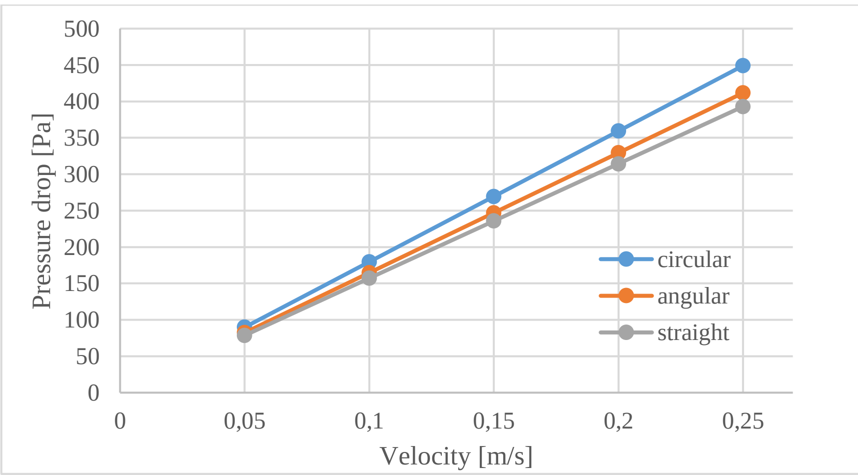

Figure 10. Variation of pressure drop

This effects can be observed for all duct geometries and is illustrated in Figure 11. Further analysis, while keeping the porosity constant, revealed that the outlet temperature of the dryer decreases as the velocity increases. The circular channel geometry demonstrated the highest outlet temperature values, which suggests that lower pump power is required to achieve the desired outlet temperature.

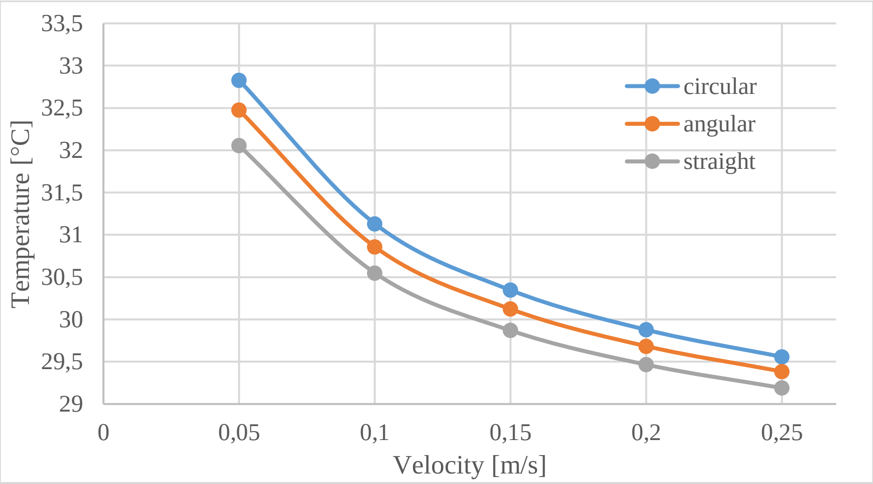

Figure 11. Variation of outlet temperature

Although the heat transfer and thus drying effect under constant porosity and permeability has been demonstrated in this way, it would be useful to continue studies involving different grain sizes and bulk effects in order to develop specific dryers.

4. Conclusion

When drying grain, conventional dryers often use ambient air that has been pre-treated. However, the geometry of the flow ducts and channels is a crucial factor in achieving optimal drying. This study examined the effects of three different channel geometries (circular, angular, and straight) on drying. The dryer medium was represented by porous media to simulate different grain sizes. The study evaluated the impact of these geometries on drying under a fixed porous media condition, analyzing five different inlet velocities ranging from 0.05m/s to 0.25 m/s. Results showed that an increase in the inlet flow rate led to an increase in pressure drop for all geometries, as expected. However, this also indicated beneficial air supply conditions for the specified dryer type. Additionally, the study noted the change in outlet temperature with pressure drop for porous media conditions representing various grain bulks. The circular duct model was found to require less pump power and result in better drying ambient conditions compared to the straight and angular models. Therefore, the study concluded that changing the duct geometry alone can lead to an improvement of over 10%. This research demonstrates the importance of studying porous media and drying air in grain drying processes, providing valuable insights for dryer design. A considerable number of studies investigating the flow and heat transfer along the flow in standard empty channel flows are available in the literature. And efforts to improve them according to fluid and channel geometries are ongoing. The study of flow with porous media conditioning is also among the popular topics of the last decade. However, studies on the channel and porosity representing grain drying need to be improved. This study reveals that many of the comparison parameters of these approaches can be used in conventional grain drying and an optimal dryer design can be developed for a given drying process.

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