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Evaluation of Solar Chimney Height Effect on the Airflow Rate and Temperature Inside the Pig House Using Computational Fluid Dynamics (CFD)

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Abstract

The aim of this study was to evaluate the effect of the solar chimney height on the temperature and the airflow rate inside the naturally ventilated pig house. Five different chimney heights were used for this study which are 0.85, 1.2, 1.70, 2.13, and 2.55 m high. For each height, temperature and airflow rate was computed using mathematical and Computational Fluid Dynamics (CFD) simulations models. In the end, CFD models results were compared to theoretical results for models' validation. The outcomes of this study showed that airflow rate increases with an increase in chimney height, showing a strong positive significant correlation ($r=0.95$, $p<0.01$) between the two parameters. Temperature on the other hand decreases with chimney height, with a strong significant negative correlation ($r=-0.97$, $p<0.01$) between the two parameters. With regards to model predictions, CFD model accurately predicted more than 95% of the data from theoretical data variation for both temperature and airflow rate. This demonstrates a strong agreement between the theoretical data and the model predicted results, while highlighting reliability of CFD model in simulating temperature and airflow distribution inside the livestock facilities accurately.

Key words: Solar chimney, CFD simulation, airflow rate, temperature distribution, natural ventilation

1. Introduction

Various parameters influence the inside thermal environment in livestock facilities, particularly pig houses given that pigs are very sensitive to thermal environment changes [1, 2]. Ventilation is a common method of keeping the indoor stable and suitable for optimal pig growth and development[3]. With the current state of energy crisis in South Africa and globally, Mechanical ventilation techniques have been deemed not only the largest consumers of energy in pig facilities but also significant contributors to the carbon footprint and negative environmental impacts [4, 5].

Solar chimney ventilation technique is regarded as the potential alternative solution to this matter as they act as an energy-free ventilation fan and emitting nearly zero greenhouse gases [6]. Solar chimney has been widely used to ventilate micro-spaces in industrial and residential buildings for thermal comfort and quality air circulation [7, 8]. This ventilation technology has spiked the interest in many researchers to investigate the working principle and significant parameters affecting the performances, such as chimney material, optimisation of installation angle, geometrical optimisation, heater absorber material etc. [9-12]. However, dimensional optimisation remains the unattended gap as very few studies have focused on chimney dimension effect on the chimney performance, particularly investigating the influence of changing the height on the ventilation rate and heat load removal.

Hence, this study aims to bridge that gap by evaluating the effect of the solar chimney height on the inside temperature and airflow rate. Airflow and temperature, alongside with humidity are the crucial environmental parameters in pig houses as they are the main factors determining thermoneutral zones. The study also aims to adopt Computational Fluid Dynamics (CFD) model to simulate the temperature and airflow distribution inside the experimental pig house across different chimney heights.

2. Materials and Methods

This section outlines the methods and materials used to evaluate the chimney height effect on the thermal environment and airflow pattern inside the pig house.

2.1. Experimental setting

Five pig housing models with varying chimney heights were developed using Autodesk Inventor 2024. The existing chimney height of 1.7 m was modified by decreasing and increasing it by 25% and 50%, respectively. For each resulting configuration, the airflow and temperature distributions inside the pig houses were determined through both mathematical calculations and CFD simulations. Consistent initial parameters and boundary conditions were applied across all simulations in order to isolate and evaluate the specific influence of chimney height on the internal thermal environment. Simulation results were evaluated against theoretical results which were obtained from theoretical calculations guided by equation 4 and 5. Figure 1 show the experimental design for the experiment of chimney height effect on the inside temperature and airflow rate.

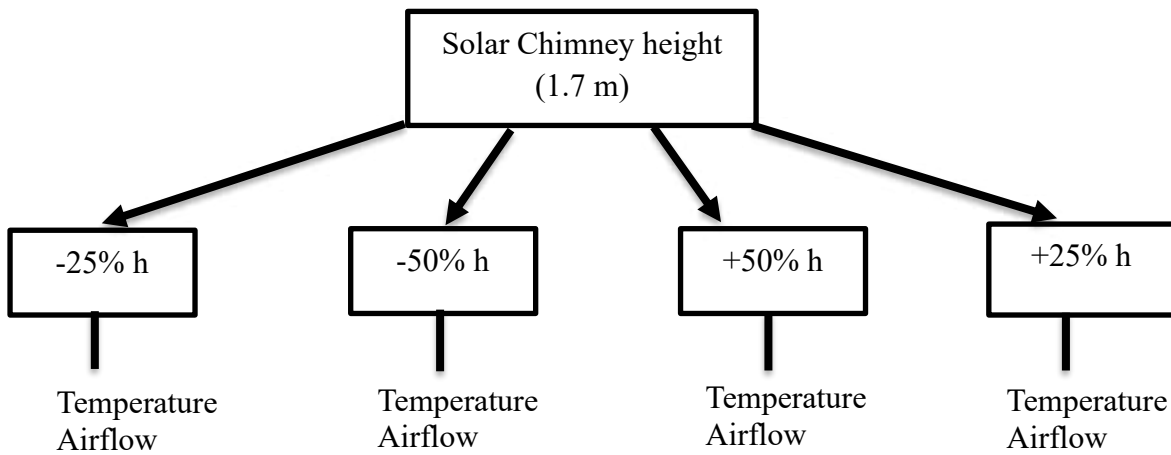


Fig.1 Experimental design to evaluate the effect of the chimney height on airflow and temperature inside the pig house

To determine the Stack pressure drive (in the chimney), Equation 1 was used, ambient temperature (T_a) and chimney temperature were measured using hobo data logger.

$$\Delta P_{drive} = \rho \times g \times h \times \frac{(T_c - T_a)}{T_a} \quad (1)$$

Where, ΔP_{drive} = Airflow driving pressure through solar chimney channel (Pa)

T_c = chimney temperature (K)

T_a = ambient temperature (K)

Assuming the steady flow, the pressure drive equals the total pressure losses which were computed using Equation 2 and 3.

$$\Delta P (friction) = f \times \frac{h \times \rho \times V^2}{2D} \quad (2)$$

Where, $\Delta P (friction)$ = Pressure drops due to friction

h = chimney height (m)

ρ = air density (kg.m^{-3})

D = chimney diameter (m)

V = air velocity through chimney channel (m.s^{-1})

f = Darcy friction factor (0.008)

$$\Delta P (minor) = K_{tot} \times \frac{\rho \times V^2}{2} \quad (3)$$

Where, $\Delta P (minor)$ = summation of minor pressure losses

K_{tot} = sum of minor loss coefficient for inlet, outlet, and bends.

Equation 4 came about combining equation 2 and 3 and therefore was used to solve for airflow rate (m.s^{-1}) through the solar chimney channel.

$$V_c = \sqrt{\frac{2\Delta P_{drive}}{\rho(f \cdot (\frac{h}{D}) + K_{tot})}} \quad (4)$$

To determine the inside temperature, equation 4 which accounts for evaporative cooling effect, sum of all heat transfers, and heat loads inside was used in all five different chimney heights.

$$T_{in} = T_a - \frac{\dot{m}C_p\Delta T_{ev}}{\dot{m}C_p + AU\Delta T} + \frac{W_{in}}{\dot{m}C_p + AU\Delta T} \quad (5)$$

Where, T_{in} = Temperature inside the pig house (K)

W_{in} = Heat load inside the pig house (W)

ΔT_{ev} = Air temperature after evaporative cooling (K)

$\dot{m}$ = mass flow rate (kg. s^{-1})

C_p = specific heat capacity of the air

2.2. Computational Fluid Dynamics simulations

Workbench 2025 R1 CFD software was used for airflow and temperature simulation in all five pig houses with different chimney sizes. Firstly, the geometry was created using Autodesk inventor, then it was imported to the ANSYS workbench software for meshing, set-up, and running the simulation. The RANS (Reynolds-Averaged Navier-Stokes) RNG-k- ϵ model was selected for simulation since it recommended for indoor airflow simulations, particularly turbulence flows.

The meshing method used was tetrahedral as it is very flexible for 3D geometries, but required finer mesh elements for accuracy, hence, the maximum mesh element size on the geometry was 0.04 mm. On the boundary section, the inlet air velocity was set to 0.95 m. s^{-1} at 22 °C as per measurements from physical experiments. Energy box and RNG-k- ϵ model were then activated to

capture temperature and turbulence airflow distribution, and a total of 2000 iterations were done to compute each simulation. The time step size of 0.025 s, with total time of 5 s, was used to evaluate the temperature and airflow profile across the indoor environment volume.

3. Results and Discussion

3.1. Solar chimney height effect on the indoor airflow and temperature analysis

Table 1 shows the theoretical results of airflow and temperature variation over chimney height calculated from Equation 4 and 5.

Table 1 theoretical airflow rate and temperature inside the pig house

Chimney height (m)	Inside temperature (°C)	Chimney airflow rate (m.s ⁻¹)
0,85	24,1	0,13
1,275	23,7	0,16
1,70	23,4	0,18
2,125	23,2	0,2
2,55	23,1	0,22

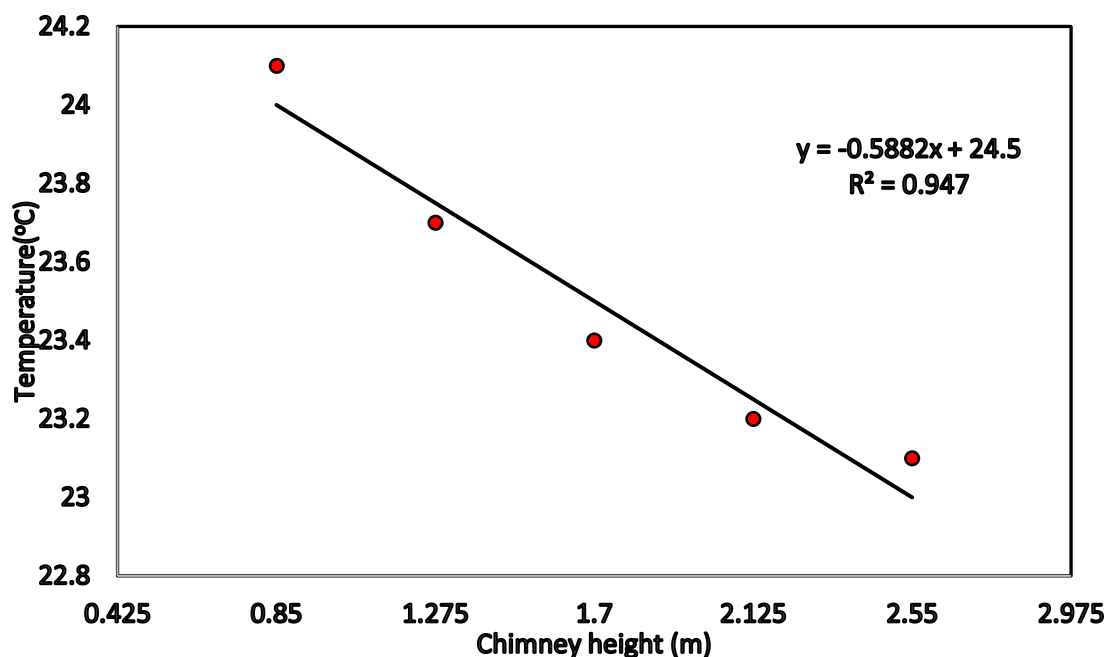


Fig.2 Regression analysis between the chimney height and indoor temperature inside the pig house

The relationship between the height of the chimney and the indoor temperature exhibited a strong significantly negative correlation ($r = -0.97$, $p < 0.01$) with a regression coefficient ($R^2 = 0.95$). These statistical measures indicates that almost all the variation occurred in the indoor temperature could be explained by the variation in the chimney height, but they also confirm increased chimney height increases stack effect and therefore improve ventilation rate and heat removal efficiency.

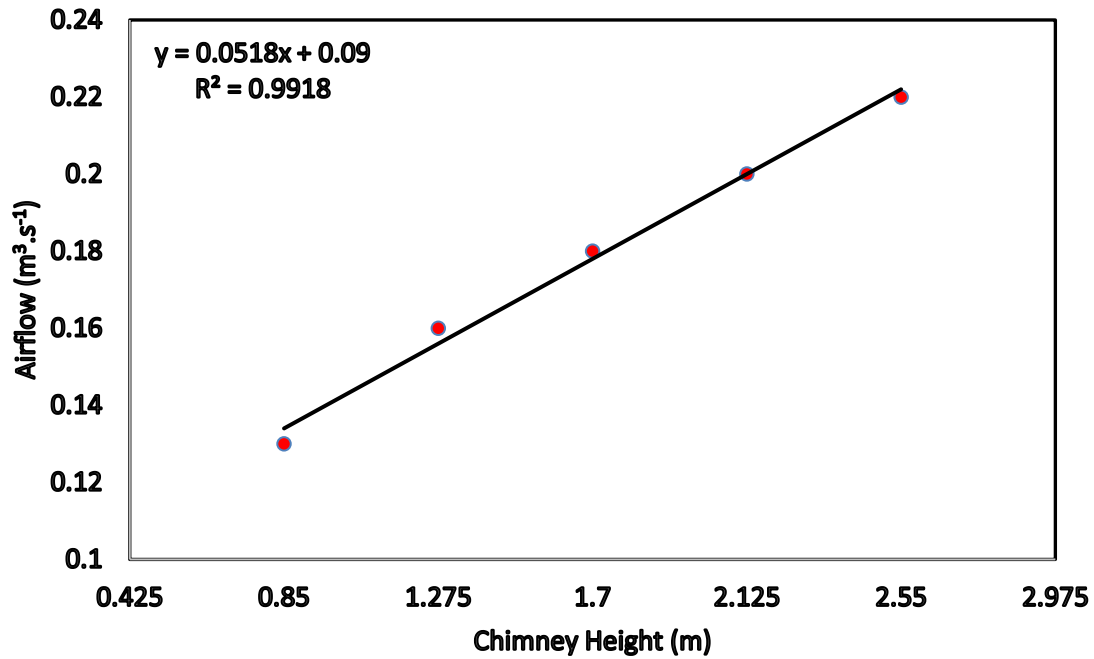


Fig.3 Regression analysis between chimney height and the indoor airflow rate inside the pig house

Conversely, chimney height and airflow rate showed a strong significant positive correlation ($r = 0.95$, $p < 0.01$) which indicate that airflow rate increased with chimney height. The regression analysis ($R^2 = 0.99$) showed that the chimney height was the dominant factor influencing the airflow rate. These results confirm that high ventilation rate is associated with taller chimney and efficient reduction of indoor thermal load. The relationship between the chimney height and both airflow rate and temperature could be explained by the stack effect phenomenon. Warm-less dense air inside the chimney rises due to thermal buoyancy, and the higher the chimney, the higher the pressure differential between chimney inlet and the outlet[13].

These results are comparable to the findings by Cuce and Cuce [14] who evaluated the chimney heights on the pressure difference and air velocity through the chimney. They found that the inlet velocity in a 100 m high chimney was 25.17 m. s^{-1} , and 18.06 m. s^{-1} in a 50 m high chimney. This also shows that 100 m chimney had higher pressure differential which resulted to higher inlet air velocity compared to 50 m chimney. In another study of performance evaluation of solar chimney draft by Ouedraogo, et al. [15], the results showed that the air velocity difference between the inlet and outlet increased with chimney height, and was always greater than 0.46 m.s^{-1} . Moreover, Setayesh, et al. [16] investigated the effect of chimney geometry on the chimney performance, and reported that 25% reduction of chimney height leads to 31% velocity decrease. Similarly, Zhang, et al. [17] found that increasing chimney height from 3 to 5 m would increase the ventilation capacity by 90%. Although majority of the findings from different researchers suggest that ventilation rate or airflow velocity increases with chimney, it must be noted that ventilation rate also depends on the solar radiation, absorptivity of the chimney materials, and other solar chimney properties. For instance, Lin and Lei [18] highlighted that the airflow rate is calculated based on solar radiation intensity, heat source intensity, and emissivity. Therefore, estimating the ventilation efficacy of a solar chimney based on incident solar radiation intensity is a convenient method, taking into account glass cover and geometry.

With regards to indoor temperature, the current study findings showed similarity with the study by Chungloo and Limmeechokchai [19] who evaluated the passive cooling system using solar chimney in hot and humid climates. They found that solar chimney can reduce the indoor temperature by 1 to 1.3 °C and by 2 to 6.2 °C when chimney height was increased. Furthermore, Yue, et al. [20] reported an inversely proportional relationship between the indoor temperature and chimney height, similar to the results of the current work.

On the energy and environmental view, improving and optimising chimney height provides a low cost, passive, and energy efficient solution to improve microclimate and thermal conditions with zero reliance on mechanical systems or any conventional cooling and ventilation systems. This approach significantly lowers the energy demand and carbon emissions in livestock facilities and agricultural practices in general. Such advancements in natural ventilation immediately benefit animal welfare, productivity, and health in the agricultural industry, especially in livestock housing, while promoting sustainable farm operations. These findings highlight the potential of solar chimney design as a crucial element of energy-efficient and climate-smart agricultural infrastructure.

3.2. Computational Fluid Dynamics model results validation

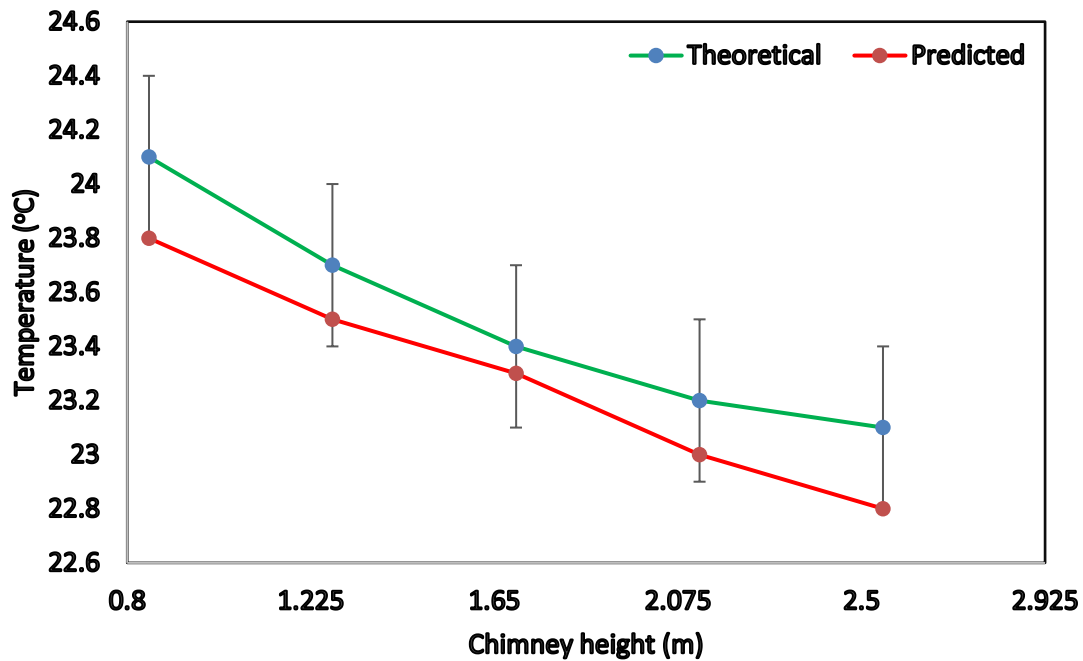


Fig.4 The correlation analysis between the model predicted inside temperature and the theoretically determined temperature

Figure 4 compares the theoretical temperature data with CFD model predicted data across five different chimney heights. Both data set exhibited a decreasing trend as chimney height increased. The standard error bars measure the uncertainty in the theoretical data. Although the model slightly underpredicts the temperature but all the model predicted temperature data lied within the standard error bars, this shows that the model correlates and agrees well with the theoretical variation which also highlights that the difference observed between the two set of data is statistically insignificant.

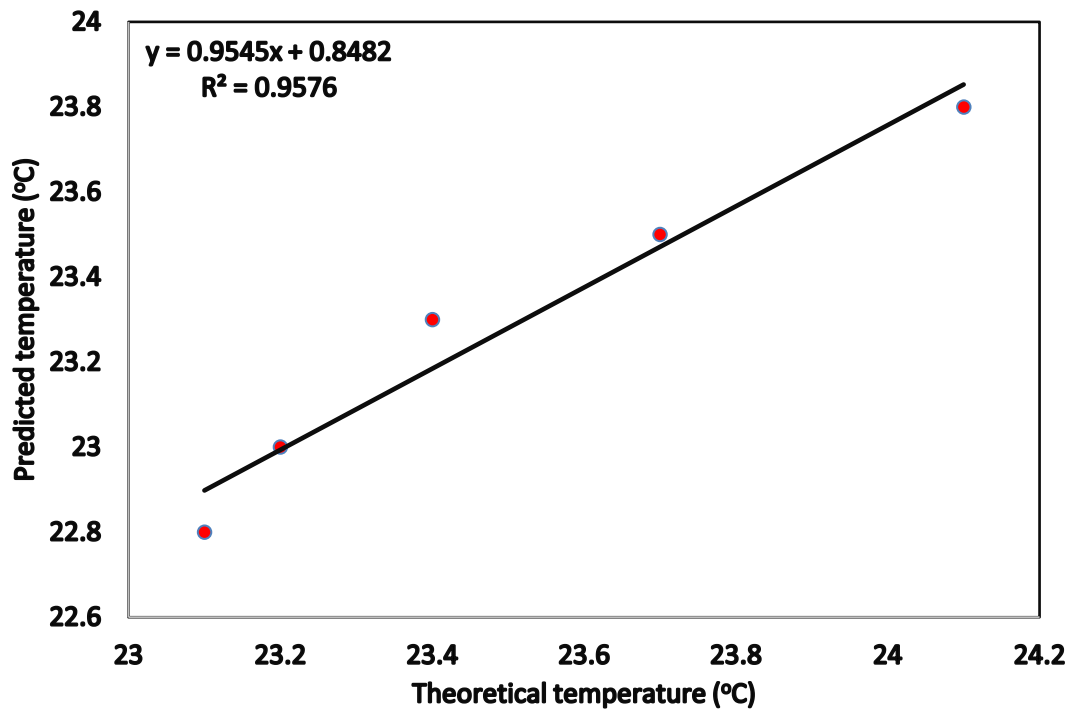


Fig.5 The agreement analysis between the CFD model predicted temperature and the theoretically determined temperature

Figure 5 shows the scatter plot measuring the extent of agreement between theoretical data set and CFD model predicted data. The results show a good strong agreement ($R^2 = 0.96$, $RMSE = 0.43\text{ }^{\circ}\text{C}$). The high coefficient of determination demonstrates that about 96% of the variation in the theoretical data set is accurately explained by the CFD model, moreover, the low prediction error ($RMSE$) indicates that numerical differences between the two data set is very minimal and negligible.

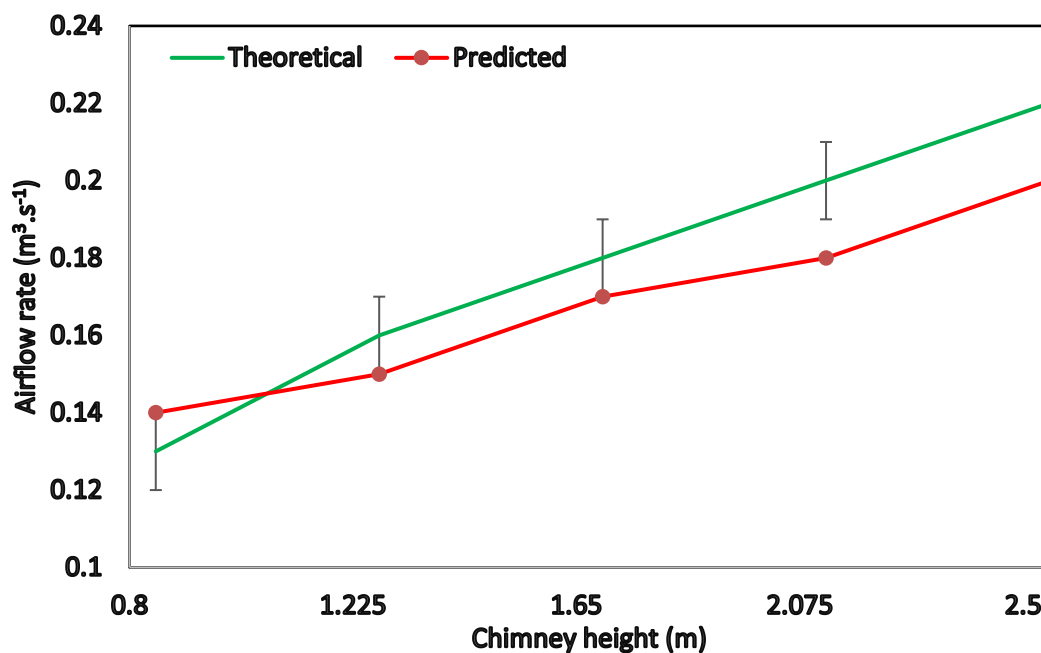


Fig.6 The correlation analysis between the model predicted inside airflow rate and the theoretically determined airflow rate

Figure 6 presents a comparison between the theoretical and model-predicted airflow rates across five chimney heights. Both datasets exhibit a general increase in airflow with rising chimney height. At lower heights, the model predictions fall within the theoretical data's standard error bounds, indicating strong agreement. However, at higher chimney heights (2.175 m and 2.55 m), portions of the predicted values extend beyond these error limits. This divergence suggests a reduction in model prediction accuracy at greater heights, resulting in a tendency to underpredict the theoretical airflow. This could require an improved boundary conditions assumption.

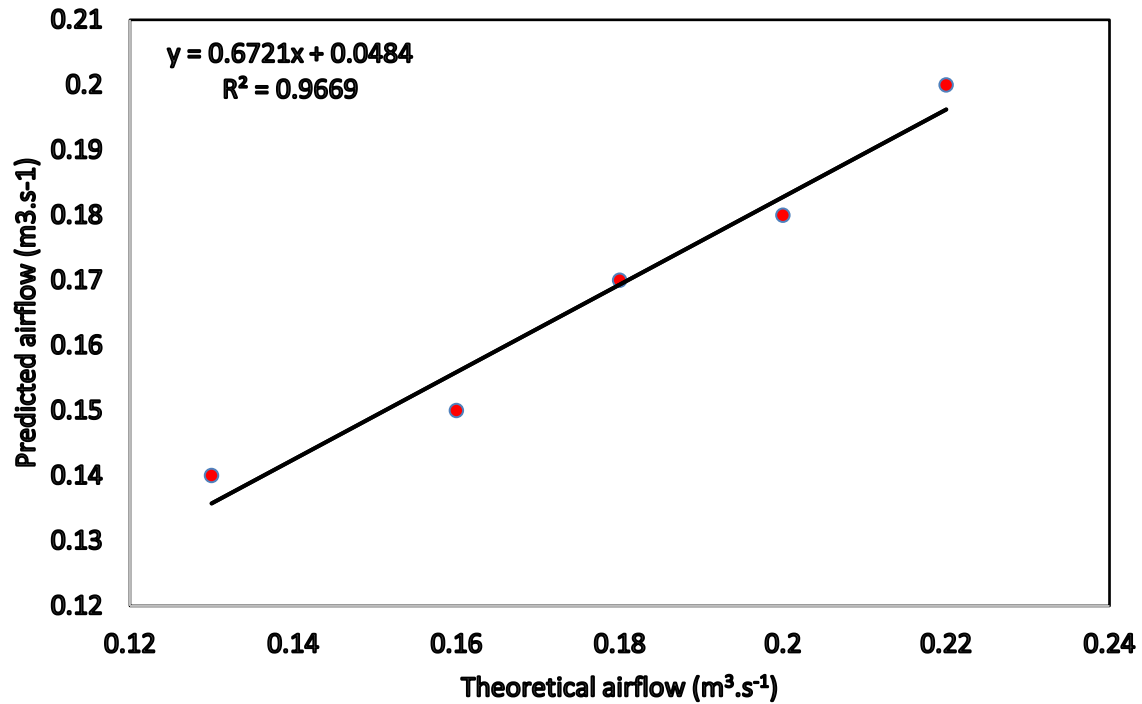


Fig.7 The agreement analysis between the CFD model predicted airflow rate and the theoretically determined airflow rate

Figure 1.7 displays the correlation between model predicted airflow and the theoretical airflow data. The results exhibit a strong agreement between the two set of data with a high coefficient of determination ($R^2 = 0.97$) showing that about 97% of the variation in the theoretical data can be explained by the CFD model. Moreover, there is a very low prediction error (RMSE = $0.01 \text{ m}^3.\text{s}^{-1}$) between the two set of data demonstrating that the difference is negligible.

The overall model predictions were very good with very minor differences observed in predicting both airflow and temperature inside the naturally ventilated pig house. However, according to Blocken and Gualtieri [21], CFD results validation is crucial since CFD modelling accuracy and dependability are dependent not only on the theoretical underpinnings but also on the user's experience, making it a theory-based and process-based method. The current study's coefficients of determination (R^2) were all greater than 95% with extremely low prediction errors, indicating the model's high accuracy. Similar outcomes were observed by Ntinis, et al. [22] who evaluated CFD models on external airflow simulation, and found that all 3 RANS models ($k-\epsilon$, RNG $k-\epsilon$ and Realizable $k-\epsilon$) agreed with the experimental data with RNG $k-\epsilon$ being the most accuracy model to predict airflow. Furthermore, Küçüktopcu and Cemek [23] found RNG $k-\epsilon$ model to be the most accurate model in predicting air speed and air temperature with RSR value of 0.19 when they were evaluating the influence of turbulence model in airflow inside the poultry house. In another, Hussain, et al. [24] evaluated RANS CFD turbulence models (standard $k-\epsilon$, RNG $k-\epsilon$, realizable $k-\epsilon$, standard

k- ω and SST k- ω) for prediction of airflow and temperature distribution and found that both RNG k- ϵ and SST k- ω best predicted the two parameters with prediction errors less than 10%. All these findings from previous and the current studies proves beyond any doubt that CFD RNG k- ϵ turbulence model is a very liable modelling tool to simulate airflow and temperature distribution which yields valid results.

Despite the growing adoption of CFD modelling in engineering applications and designs, many researchers have highlighted the flaws of RANS models and argues that Large Eddy Simulations (LES) provides more accurate results than RANS models, thus they should be mostly used over RANS model to improve results reliability [25-29]. Moreover, CFD users are still required to accurately determine numerous parameters that are crucial for accuracy of the simulation which also increase results unreliability due to potential human errors[30, 31]. These parameters include the boundary conditions, computational domain and mesh, discretization schemes, convergence criteria etc. [32]. However, the main reason behind RANS models domination despite their low accuracy as opposed to high accurate LES, is that LES requires a finer computational mesh and more resources than RANS [33]. Although LES has potential uses in engineering design and industry, it is still too computationally expensive to do routine simulations [34]. Hence, RANS remains the most extensively used modelling methods that resolve fluid flows and temperature distribution problems. Such arguments demonstrates that there is still a need to develop more advanced models that would provide optimal balance between the computational costs, human inputs, and model accuracy.

3. Conclusion

The purpose of this study was to evaluate the chimney height effect on the temperature and airflow rate inside the pig house using theoretical and CFD simulations methods. The study used RANS models (RNG k- ϵ) to assume turbulence flow to accurately simulate the actual temperature and airflow distributions. Both methods yielded similar results, as they showed that temperature inside the pig house decreases with an increase in the chimney height. Furthermore, airflow rate increases with an increase in the chimney height. This trend is attributed to high pressure differential that occurs as chimney height increases. High pressure difference creates that suction pressure that drives the airflow from the inside and exhaust it through the chimney, thus improving the airflow that and consequently removes the heat load out of the pig house efficiently. The model results were compared to theoretical results and both data set showed a strong agreement with the small error margins of 0.01 m³.s⁻¹ and 0.43 °C for airflow rate and temperature, respectively. Overall, these findings emphasise the significance of chimney height as a design parameter for increasing natural ventilation efficiency in pig housing. The proven CFD technique not only provides a dependable tool for optimising ventilation systems, but it also provides practical insights that can support the development of cost-effective and energy-efficient livestock facilities in modern agricultural engineering. This work thus adds relevant knowledge that can help engineers, designers, and farmers to improve animal welfare and reduce the operational energy footprint in livestock production environments.

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Authors' contributions

Material preparation, Modelling, and data analysis were all performed by S.Z. The first draft of the manuscript was written by S.Z while TS and SS proofread and edited it. All the authors have read, approved, and agreed on the published manuscript version.

Consent for publication

Not applicable

Conflict of interests

The author declares that they have no competing interest.

Clinical trial number

Not applicable.

Data availability

All data generated or analysed during this study are included in this published article.

Ethics and Consent to participate

Not applicable

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