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Effects of Particle Diameter and Permeability on Air Cooling Performance of a Porous Bed

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ABSTRACT

This study investigates varying particle diameters and porosity to improve the cooling performance of a porous bed. It also considers actual and scaled-down clinker bed sizes. The result from the study was validated with existing data from actual-size clinker beds. For the actual size, predicted air outlet temperature, when compared to the experimental and numerical simulation results produced deviation of –5.46% and +1.65% respectively. For the scaled down-sizes, the air outlet temperature when compared with the actual size of experimental result, yielded deviations of 3.96% and 4.9% because the scaled sizes have 3 and 9 scale factors, respectively. The initial increase in air outlet temperature was minimal, but as the diameter increased, the temperature reduction became significant. The rate of air outlet temperature decrease was slightly consistent from 0.1 to 0.5, but widens as porosity increases. However, as porosity increases, the rate widens. Furthermore, it was discovered that, the heat transfer rate between air and clinker decreases less significantly between diameters of 0.01 to 0.02 m, but increases as porosity increases to 0.6, 0.7, and 0.8, resulting in a significant reduction. The study concluded that as clinker particle diameter increases, outlet temperature also increases, pressure drop decreases, with a significant decrease observed between 0.01 and 0.02 m and porous bed with scale factor 9 had high pressure drop values as the other three bed sizes showed similar results.

INTRODUCTION

Heat transfer and airflow process can be considered as an integral process in industries where high temperature is required to be cooled down to non-destructible temperature. One such industry is the cement plant, where clinker is required to be cooled down for further processing and packaging. Heat transfer is primarily required to offset heat from high-temperature solid materials. These high-temperature solid materials are common intermediate products e.g. ceramic granules and cement clinkers, which need to be cooled down for further processing or transportation (Shao *et al.*, 2020). The cement production process unit basically consists of the preheater with calciner, the rotary kiln and the clinker cooler (Okoji *et al.*, 2021). During cement production, heat transfer occurs due to the heating or cooling of materials, with the goal of producing efficient and reliable cement products for distribution to end-users. Energy utilization in the global cement industry accounts for about 40 to 60% of the production cost (John, 2020), and cement, being the final product, is the most manufactured product on earth (Hanein *et al.*, 2020). Clinker is the fundamental component of the cement, produced through a baking process in a kiln and a subsequent cooling process in a clinker cooler (Alsop, 2019). Clinker coolers are important equipment in cement industry that recover heat from the hot clinkers by passing cooling air through the grate plates of the grate cooler upward through the pore space of the clinker bed (Cao *et al.*, 2016), thereby cooling down the hot clinker to a non-destructible temperature. In industrial applications where very large-sized equipment are used, for example the clinker cooler in cement plants, a reliable scaling down is required to reduce the size of the clinker cooler or clinker porous bed to give a replica of the real size of the clinker bed that can be modeled easily. The reduction in size can be achieved through similarity theory. Similarity (Similitude) theory refers to the theory and art of predicting prototype conditions from model observations by prescribing the relationship between full-scale flow and a flow involving smaller but geometrically similar boundaries (Kumar, 2010). Coutinho *et al.* (2015) defined similitude theory as a branch of engineering science concerned with establishing the necessary and sufficient conditions of similarity among phenomena. Similarity helps engineers and scientists to accurately predict the behavior of prototypes, through scaling laws applied to the experimental results of a scale model related to the prototype by similarity conditions (Coutinho *et al.*, 2015; Altun *et al.*, 2020). In designing and producing a prototype model based on a small-scale model, the prototype model is designed based on the similarity law, which establishes dimensionless factors for geometric shape, properties and flow characteristics between prototype and small-scale models (Yoon et al, 2020). Dimensional analysis offers identification of groups of variables whose interrelationships may be determined experimentally (Douglas *et al.*, 2013). It is the basis of similarity theorem and is preferred because it is simple and fast to apply in problems where equations and boundary conditions cannot be fully expressed and not always helpful (Casaburo *et al.*, 2019; Kenan and Azeloglu, 2020). In recent years, to overcome the obstacles associated

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with full-scale testing, such as cost and setup, research on similitude methods expanded into many branches of engineering (Casaburo *et al.*, 2019). The application of analytical methods and similarity theorem has therefore paved way for detailed investigation in the performance of porous materials such as the cement clinker. In order to avoid these risks and losses, it is important to understand how the geometrical and process parameters can be optimized to improve the cooling performance of the clinker cooler. Studies have shown that with extensive investigation on clinker coolers, the temperature of hot clinker could be reduced to as low as 100°C (Ahamed *et al.*, 2012). Yet, effects of particle diameter and porosity on the thermal and hydraulic performance have not been adequately investigated (Shao *et al.*, 2020). These factors play significant roles in the cooling process of real-life applications; however, it is not economically viable to investigate them in real-life clinker coolers, considering their sizes and losses incurred by stopping production. Hence mathematical analysis become a viable approach for actual size and scaled size.

MATERIALS AND METHODS

Data obtained from Cui *et al.* (2017) which had been validated with experimental study, was adopted. The mathematical modeling of the grate clinker cooler considers the cooling to be in steady-state condition, with a cross flow heat exchange between hot clinker particles and cooling air mostly at ambient temperature. In modeling the cooling process, heat transfer and pressure drop are defined by mathematical equations (Shao et al 2017; Touil *et al.*, 2015). In order to achieve the development of the mathematical model, some assumptions were made. The assumptions are as follows (Shao *et al.*, 2017; Touil *et al.*, 2015): clinker bed consists of homogenous spherical clinker particles; the temperature of hot clinker at rotary kiln exit is the same at cooler inlet; air flows vertically upwards through the clinker, quantities of fine particles transported by air flow are negligible and radiation heat transfer is not considered.

Heat transfer rate between cooling air and clinker is given by equation (1) (Shao *et al.*, 2017; Idowu *et al.*, 2024):

$$Q=\Delta T_{diff}\times(1-q)/(1/C_{air}-[q/C_{clk}]) \tag{1}$$

where: term ΔT_{diff} is the difference between clinker inlet and air inlet temperatures, Q is the heat transfer rate (J/s) C_{clk} is the ratio of heat capacity rates of clinker (W/K) and C_{air} is the ratio of heat capacity rates of cooling air (W/K).

The term ΔT_{diff} is the difference between clinker and air inlet temperatures, estimated using equation (2):

$$\Delta T_{diff}=T_{clkin}-T_{airin} \tag{2}$$

The term C_{clk} in equation (1) is the ratio of heat capacity rates of clinker and is estimated using equation (3):

$$C_{clk}=m_{clk}\,C_{pclk} \tag{3}$$

The velocity of clinker is estimated using equation (4):

$$U_{clk}=m_{clk}/(HW\varrho_{clk}) \tag{4}$$

The ratio of heat capacity rates of cooling air is estimated using equation (5):

$$C_{air}=m_{air}\,C_{air} \tag{5}$$

The superficial velocity of air is estimated from equation (6):

$$U_{air}=m_{air}/(LW\varrho_{air}) \tag{6}$$

The term q is estimated using equation (7):

$$q=\exp(kA[(C_{air}-C_{clk})/(C_{air}C_{clk})]) \tag{7}$$

where: T_{clkin} is the temperature of clinker at inlet of the cooler (°C), T_{airin} is the temperature of air at inlet of the cooler (°C), ϱ_{air} is the density of air (kgm^{-3}), m_{clk} is the mass flow rate of clinker (kg/s) and C_{pclk} is the specific heat capacity of clinker (J kg$^{(-1)}$ K$^{(-1)}$), U_{air} is the superficial velocity of air (m/s), U_{clk} is the velocity of clinker (m/s), L is the length of clinker bed (m), W is the width of clinker bed (m), C_pair is the specific heat capacity of clinker (J kg$^{(-1)}$ K$^{(-1)}$), k is the integrated heat transfer coefficient (W/m^2/K) and A is the efficient heat transfer area (m^2)

The integrated heat transfer coefficient between cooling air and clinker, is given by equation (8) (Shao *et al.*, 2017):

$$k=1/(1/h+\varphi x/\lambda_{clk}) \tag{8}$$

Convective heat transfer coefficient between cooling air and clinker is given by equation (9) (Shao *et al.*, 2017a):

$$h=(Nu\lambda_{air})/D_p \tag{9}$$

Nusselt number is obtained using equation (10) (Cui *et al.*, 2017):

$$Nu=2+1.8\,Pr^{(1/3)}_{air}\,Re^{(1/2)}_{air} \tag{10}$$

Reynolds number of air is given by equation (3.11):

$$Re_{air}=(\varrho_{air}\,U_{air}\,D_p)/\mu_{air} \tag{11}$$

Prandtl number of air is given by equation (12):

$$Pr_{air}=(\mu_{air}\,C_{pair})/\lambda_{air} \tag{12}$$

where: h is convective heat transfer coefficient (Wm$^{(-2)}$ K$^{(-1)}$), φ is the particle shape correction factor, taken to be 0.25, x is the clinker particle heating depth which is equal to the radius of clinker particle (m), λ_{clk} is the thermal conductivity of clinker particle (Wm$^{(-1)}$ K$^{(-1)}$), μ_{air} is the kinematic viscosity of air (kgm$^{(-1)}$ s^{1}), D^p is the average diameter of clinker particle (m), U_{air} is the superficial velocity of air (ms$^{(-1)}$) and λ_{air} is the thermal conductivity of air (Wm$^{(-1)}$ K$^{(-1)}$) .

The effective heat transfer area between cooling air and clinker particle is given by equation (13):

$$A=(6V_{clk}\,(1-\varepsilon))/D_p \tag{13}$$

The volume of clinker bed is equation (14):

$$V_{clk}=LWH \tag{14}$$

The clinker cooling process is simplified as a direct heat exchanger; hence the heat balance equation is applicable and expressed as (Shao et al 2017):

$$C_{clk}\,(T_{clkin}-T_{clkout})=Q=C_{air}\,(T_{airout}-T_{airin}) \tag{15}$$

Equation (15) can also be expressed as:

$$Q_{clk}=Q=Q_{air} \tag{16}$$

Clinker outlet temperature can be determined using equation (17):

$$T_{clkout}=T_{clkin}-Q_{clk}/C_{clk} \tag{17}$$

Air outlet temperature can be determined using equation (18):

$$T_{airout}=T_{airin}+Q_{air}/C_{air} \tag{18}$$

The pressure drop of cooling air across the bed is estimated using equation (19) (Shao *et al.*, 2017):

$$(\Delta P_{air})/H=[(150\mu_{air})/\,D^2_p\times(1-\varepsilon)^2/\varepsilon^3\times U_{air}]+[(1.75\varrho_{air})/$$

$$D_p \times (1-\varepsilon)/\varepsilon_3 \times U^2_{air}] \quad (19)$$

where: ε is the porosity of the clinker bed, H is the height of clinker bed (m), ϱ_{air} is the density of air (kgm$^{(-3)}$), ΔP_{air} is the pressure drop of cooling air (Pa), ε is the porosity, U_{air} is the superficial velocity of air (m/s).

The thermo-physical properties of air and clinker are given as follows (Idowu *et al.* 2024).

$$\varrho_{pair}=(351.99/T_{air})+(344.88/T^2_{air}) \quad (20)$$

$$C_{pair}=955+0.14387T_{air}+3.8525\times10^{(-5)}\ T^2_{air}+2.1036\times10^{(-10)}\ T^3_{air}+1.2052\times 10^{(-13)}\ T^4_{air}\ (J\ kg^{(-1)}\ K^{(-1)}) \quad (21)$$

$$C_{pclk}=699.5+0.31812T_{clk}-6.2308\times10^{(-5)}\ T^2_{clk}-1.3753\times10^{(-10)}\ T^3_{clk}-5.1388\times10^{(-14)}\ T^4_{clk}\ (J\ kg^{(-1)}\ K^{(-1)}) \quad (22)$$

$$\lambda_{air}=0.0244(T_{air}/273)^{0.759}(Wm^{(-1)}\ K^{(-1)}) \quad (23)$$

$$\lambda_{clk}=0.244[1+0.00063(T_{clk}-273)]\ (Wm^{(-1)}\ K^{(-1)}) \quad (24)$$

$$\mu_{pair}= 1.72\times 10^{(-5)}\ [(273+114)/(T_{air}+114)]\ (T_{air}/273)^{1.5}\ (kgm^{-1}s^{-1}) \quad (25)$$

Table 1: Properties of Actual Size of Clinker Bed

Parameter	**Symbol**	**Unit**	**Idowu *et al.* (2024)**	**Cui *et al.* (2017)**
Clinker inlet temperature	T_{clkin}	°C	1365	1365
Clinker outlet temperature	T_{clkout}	°C	870.7	-
Air inlet temperature	T_{airin}	°C	30	30
Air outlet temperature	T_{airout}	°C	1096.9	1079.06
Clinker mass flow rate	m_{clk}	kgs$^{(-1)}$	72.32	72.32
Air mass flow rate	m_{air}	kgs$^{(-1)}$	35.17	35.17
Average diameter of clinker	D_p	m	0.04	0.04
Width of clinker bed	W	m	4.00	4.00
Height of clinker bed	H	m	0.75	0.75
Length of clinker bed	L	m	3.26	3.26
Porosity	ε	-	0.4	0.4

RESULTS AND DISCUSSION

The mathematical equations were implemented in MatLab software to compute the compute air and clinker temperature at outlet of the clinker bed. Additionally, air pressure drop across the height of the clinker bed was also computed. In order to establish the reliability of the mathematical solutions, the results obtained for the actual size and scaled-down sizes were compared with results obtained from the work of Cui *et al.* (2017) for both the experiment and simulation. After validation, more results were computed for varied clinker particle diameter and porosity of clinker bed.

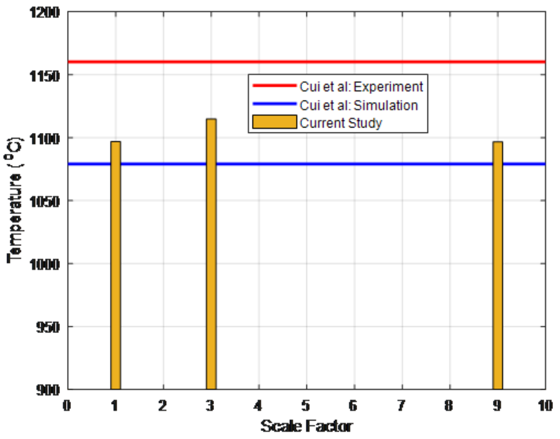

Figure 1: Validation of mathematical solution

In order to validate the mathematical equations employed for estimating the performance of the clinker bed during cooling, air outlet temperature after cooling of clinker bed obtained from experimental and numerical study in the work of Cui *et al.* (2017) is compared with air outlet temperature obtained from the mathematical equations in this study. It should be noted that aside from comparing the temperature obtained for actual size of clinker bed, scaled down sizes were also compared and the results presented in figure 1. As seen in the figure, the results from this study were represented with bar, for scale factors 1, 2 and 3, where scale factor 1 represent the actual size of the clinker bed. From the graph, the air outlet temperatures estimated for the three scaled sizes fall between the obtained temperatures from the experiment and the numerical study reported in the work of Cui *et al.* (2017). For the actual size, predicted air outlet temperature, when compared to the experimental and numerical simulation results from Cui *et al.* (2017), produced deviation of –5.46% and +1.65% respectively. For the scaled down-sizes, the air outlet temperature when compared with the actual size of experimental result, yielded deviations of 3.96% and 4.9% because the scaled sizes have 3 and 9 scale factors, respectively.

Effect of Clinker Particle Diameter on Cooling Performance

The particle diameter of a porous material is an important parameter that must be investigated in order to gain deeper understanding of how variation in its geometrical property affects the cooling performance of the clinker cooler. In view of this, the diameter of the clinker particle was varied to determine how they influence the cooling performance of the clinker cooler. The clinker particle diameter was varied from 0.01 m to 0.08 m at interval of 0.01 m. Comparison between the scaled sizes 1, 3 and 9 were presented going forward, considering that the mathematical equations have been validated. Moreover, experimental data are not available due to the cost of performing experimental study in the cement with respect to variation of clinker diameter. It should also be noted that the diameters presented in the graphs are for the actual size of clinker particles, while the corresponding values for scaled sizes 3 and 9 are presented in table of appendices. Additionally, the location of points for air outlet temperature at each scaled size represent the actual corresponding estimated values.

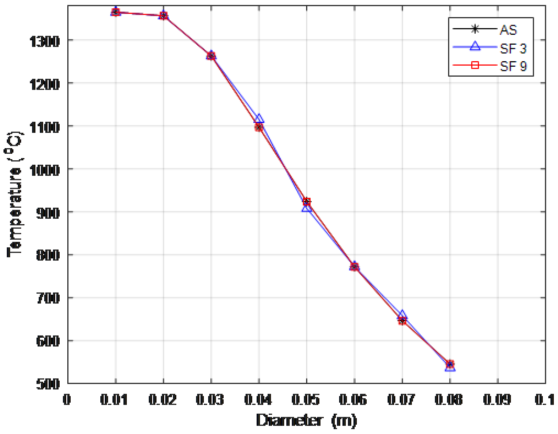

Figure 2: Diameter Vs air temperature

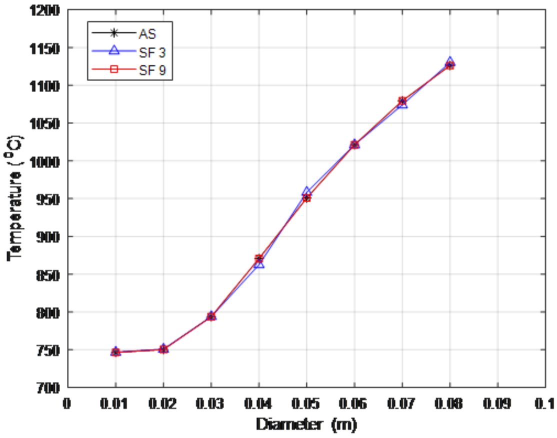

Figure 3: Diameter Vs clinker temperature

Figure 2 shows the variation of air outlet temperature with increase in diameter. It can be seen that as the clinker diameter increases, the air outlet temperature decreases. At the initial increase from 0.01 m to 0.02 m, the reduction in temperature was minimal (< 100 °C). However, as the diameter increases from 0.02 m at fixed interval, the temperature reduction appears significant (> 100 °C) and kept reducing to the last diameter of 0.08 m considered. As the air exits the clinker cooler, a corresponding effect is achieved at the clinker outlet. Hence, the effect of the same range of clinker particle diameter is presented in figure 3. It can be seen that as the clinker diameter increases, the clinker outlet temperature increases. Increase in clinker outlet temperature is not desirable because the primary objective of the clinker cooler is to cool down the very hot clinker entering the cooler. However, a similar minimal increase was observed between clinker particle diameter of 0.01 m and 0.02 m.

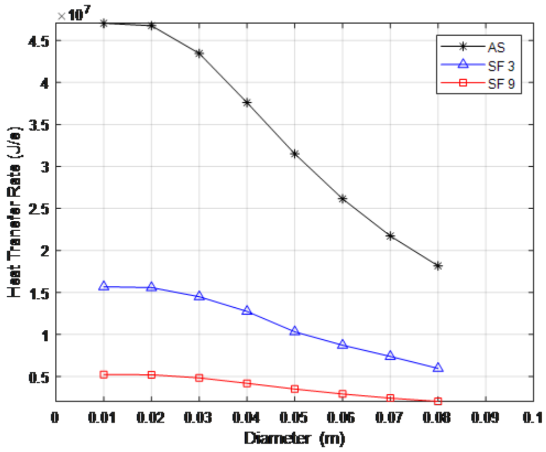

Figure 4: Diameter Vs heat transfer rate

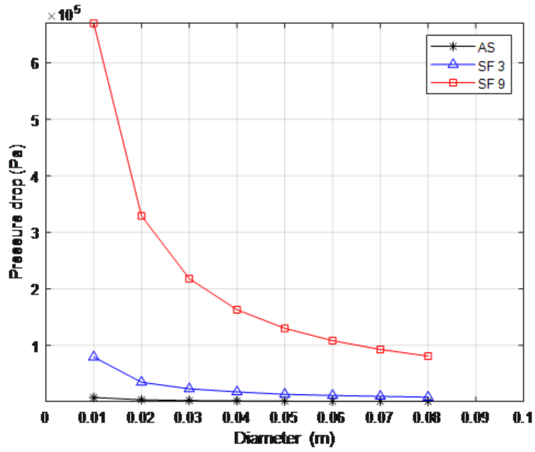

Figure 5: Diameter Vs pressure drop

Figure 4 illustrates the effect of variation of clinker diameter on heat transfer rate. Heat transfer rate is an important parameter in understanding the cooling process taking place in operation any heat exchanger. A clinker cooler is a typical heat exchanger which operates in a crossflow process, exchanging heat been hot solid particles (clinker) and cold gas (air). Firstly, the performance observed in terms of increase in clinker particle diameter for the difference sizes showed that heat transfer rate decreases as the clinker particle diameter increases. Interestingly, it was observed that between diameter of 0.01 to 0.02 m the decrease was not significant compare to the cases with higher clinker diameter above 0.02 m. More so, for the scaled size with scale factor 9 (smallest size of clinker bed), the decrease in heat transfer rate appears to be negligible. Another important observation is the trend in decrease with respect to size of clinker bed, whereby reduction in size resulted to significant reduction of heat transfer rate at each clinker particle diameter. The effect of clinker particle diameter on air pressure drop was also studied and the performance presented in figure 5. Increase in pressure drop is not desirable as it leads to increase in pumping cost which increases the general production cost of cement. From the figure, it can be seen that as the diameter of clinker particle increases, the pressure drop decreases. This performance implies that when considering reduction in pumping cost, large diameter of clinker particle will be desirable. Interestingly, the decrease in pressure drop was more significant between clinker particle of 0.01 and 0.02 m. When the diameter increases above 0.02 m, the pressure drop decrease was not highly significant as the case between 0.01 and 0.02 m. Deduction from these performances implies that optimum particle diameter is approximately 0.02 m.

Effect of Porosity Cooling Performance

In addition to the effect of particle diameter of clinker, the effect of porosity of clinker bed on heat transfer rate, temperature and pressure performance of the clinker cooling process was also investigated. The porosity of the clinker bed was varied from 0.1 to 0.8 at interval of 0.1. Additionally, the performance comparison as considered scaled sizes of the clinker bed.

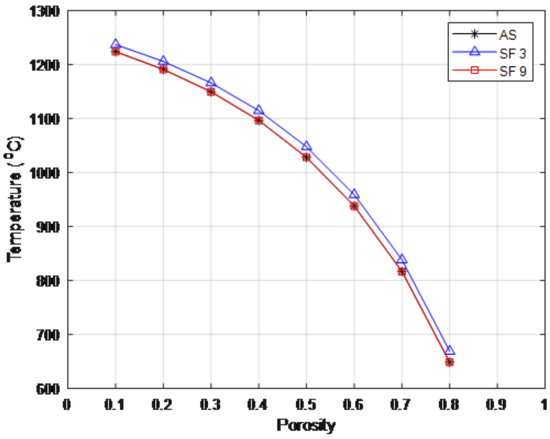

Figure 6: Porosity Vs air temperature

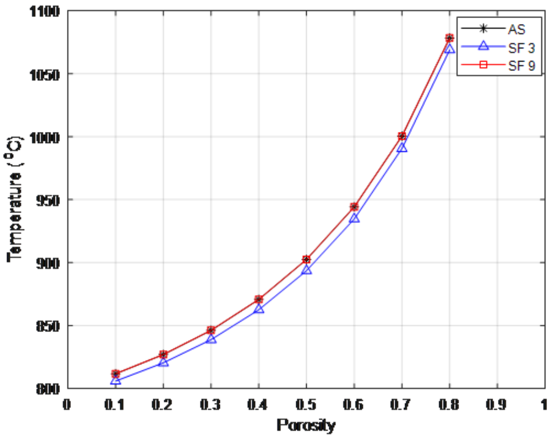

Figure 7: Porosity Vs clinker temperature

Firstly, the performance of the porosity of clinker bed was investigated for the air outlet temperature after cooling, presented in figure 6. As observed in the figure, increasing the porosity decreases the air outlet temperature. The rate at which the clinker outlet temperature decreases was observed to be slightly consistent from porosity of 0.1 to 0.5. However, as the porosity was further increased at the same interval to 0.6, 0.7 and eventually 0.8, the rate of decrease in air temperature widens. When comparing this performance for the three different scale down sizes, similar trend was observed. Although, clinker bed with scale factor 3 produced higher values of temperature at each porosity. The performance of the actual size and the scaled down size with scale factor 9 was very close, indicating negligible difference. The performance of the clinker outlet temperature was also recorded. Based on the cross-flow heat exchange cooling principle employed, it is expected that as the air outlet temperature decreases with increase in porosity, the clinker outlet temperature will increase with increase in porosity.

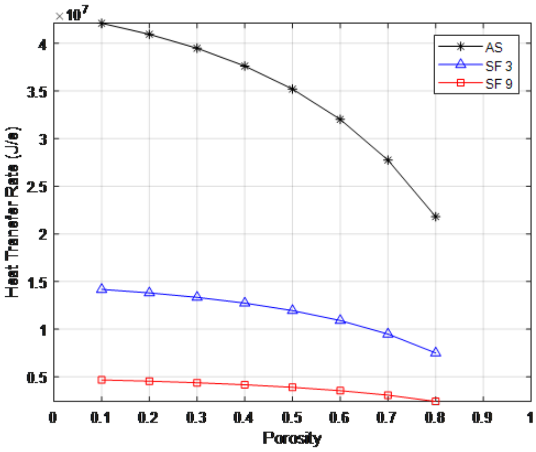

Figure 8: Porosity Vs heat transfer rate

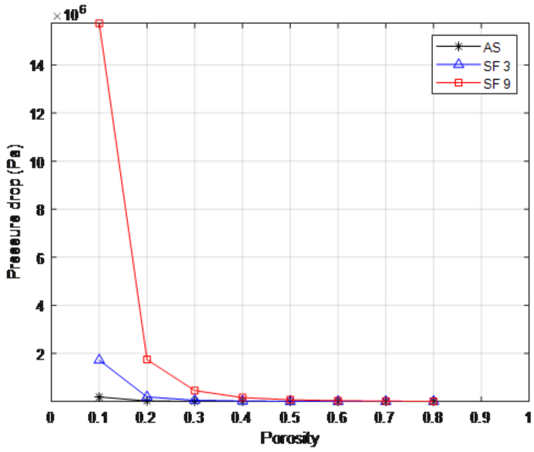

Figure 9: Porosity Vs pressure drop

The effect of variation (increase) of porosity of clinker bed on heat transfer rate was also considered, and the performance presented in figure 4.8. The performance trend observed from the figure showed a decrease in heat transfer rate with increase in porosity. The decrease in heat transfer rate takes a non-linear trend from the initial porosity (0.1) to the final porosity (0.8). A similar trend as seen for the increase in clinker particle diameter was also observed such that the rate at which the heat transfer rate decreases was slightly consistent from porosity of 0.1 to 0.5. But as the porosity increases at the same interval to 0.6, 0.7 and eventually 0.8, the rate of increase in heat transfer rate widens. Furthermore, the trend in decrease with respect to size of clinker bed, revealed that reduction in size resulted to significant reduction of heat transfer rate at each porosity. The pressure drop performance of the clinker bed with variation in porosity was also studied and the result presented in Figure 4.9. Firstly, it was observed that at porosity of 0.1, the clinker bed with scale factor of 9 produced very high value when compared to the bed with actual size and size of scale factor 3. Secondly, for the three bed sizes, the pressure drop decreases with increase in porosity. Thirdly, as the porosity increases, the pressure drop value estimated were very close with negligible difference.

CONCLUSIONS

In this study, a theoretical study was carried out, varying the diameter of clinker particles and porosity to determine how they affect the temperature and pressure drop performance after cooling. Actual size and scaled-down sizes of clinker beds were considered to also establish the potential of exploring different sizes of clinker beds for laboratory-scale experimental study and numerical simulation. The results from mathematical modelling of the cooling process were validated with experimental and numerical study of actual size clinker bed of a clinker from literature. The temperature decrease appears to be substantial when the diameter increases from 0.02 m at a set interval and continues to decrease until the final diameter of 0.08 m is taken into consideration. The rate at which the air outlet temperature drops was found to be somewhat constant for porosities ranging from 0.1 to 0.5. The clinker outflow temperature rises in proportion to the clinker diameter. Between 0.01 m and 0.02 m, there was a little rise in clinker particle diameter. Additionally, the performance showed that the rate of decline in the clinker outlet temperature was somewhat constant across porosities of 0.1 and 0.5. However, the rate at which the clinker outlet temperature rises increases when the porosity rises at the same interval to 0.6, 0.7, and ultimately 0.8. The reduction in heat transmission rate seems to be minimal for the minimum size of clinker bed, which is scaled with scale factor 9. However, the rate of increase in heat transfer rate widens when the porosity rises at the same interval to 0.6, 0.7, and ultimately 0.8. The heat transmission rate at each porosity was significantly reduced as a result of the size reduction. The pressure drop decrease was not as dramatic as it was between 0.01 and 0.02 m when the diameter increased above that point. When compared to beds of actual size and size of scale factor 3, it was found that the clinker bed with a scale factor of 9 yielded exceptionally high values at a porosity of 0.1.

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