Transport Phenomena in Pilot Curing Process of Coal and Bio-Coal Briquette

Vorrasit Tralelape, Monpilai H. Narasingha, and Karn Pana-Suppamassadu

***Abstract*—To develop the curing unit for coal and bio-coal briquette with a proper design, the raw-materials and product characteristics and optimum curing conditions, including transport phenomena within the unit should be taken into consideration. In this study, the effects of briquette shape, and type and composition of biomass presented in the bio-coal briquette should have on transport phenomena involved in a pilot scale curing unit were investigated via a computational approach i.e., Finite Element Scheme. From the simulation results, it is clear that the shape of briquette plays a vital role in moisture removal during the curing process. The heat transfer is found to rely strongly on conditions at the briquette surface, while the mass transfer depends on the physical properties inside the briquette, which in turn depending on shape. When compare the bio-coal briquette with the coal one, the heat and mass transfers as occurred in the bio-coal briquette have remarkably similar characteristics to those of the coal briquette but the rates. This difference in rates of heat and mass transfers of these briquettes is due to their differences in apparent physical and transport properties.**

***Index Terms*—Bio-coal briquette, curing, effect of biomass**

I. INTRODUCTION

Over recent years, a co-firing biomass with coal has gained great attention with an attempt to reduce net CO_2 and SO_2 emissions from coal-based power plants. To do so, the bio-coal briquetting technology is essential among the technologies associated with co-combustion of biomass and coal, and it offers a low-cost and environmentally friendly option since the raw materials are normally coal fines (waste) and agricultural wastes. It is estimated that the biomass, including municipal solid waste, can contribute nearly 43% of the total energy required for the developing countries and 26% for some developed countries [1].

Being part of the briquetting technology, the curing process is also an essential step of briquetting, in which the significant mechanical [2] and physico-chemical properties of the products will be improved. To design an appropriate curing unit for the briquetting process, raw-materials and product characteristics and optimum curing conditions, including transport phenomena within the unit, are all taken into consideration. From the previous work [3], a lab-scale curing unit was designed based on information obtained for coal briquette in a soap-like shape. However, the involved transport phenomena that occurred inside the unit must be further investigated to provide more insight about the curing and also for other prospective shapes. The briquette shapes of interest in the study are spherical, cylindrical, cubical, and soap-like. Thus, it is the major purpose of this study to apply the computational technique to study the transport phenomena under the influence of shape of briquette and type and composition of biomass used in briquetting.

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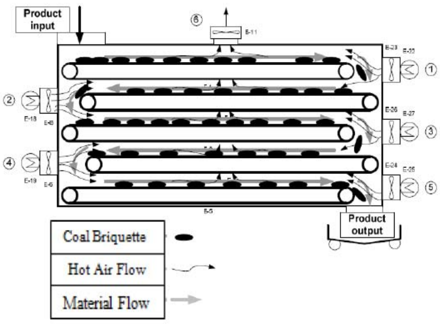
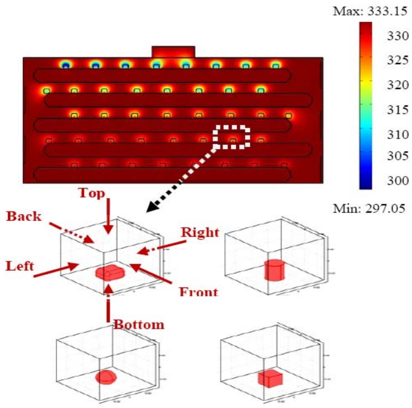
II. DESCRIPTION OF COAL CURING UNIT

In this work, the curing unit for coal and bio-coal as shown in Fig.1 (a) and the thermodynamics and operating conditions such in Fig.1 (b) will be referred to. The detailed simulations were conducted for various shapes and types of briquette in the sub-domains as appeared in Fig. 1(b).



(a)



(b)

Fig. 1. Bio-coal curing unit: (a) material and hot air streams (b) temperature distribution at the operating condition of curing process and the simulation subdomains.

III. COMPUTATIONAL SETUP

A. Hydrodynamics of Hot Air

$$\rho\frac{\partial u}{\partial t}-\nabla.\eta\left(\nabla u+(\nabla u)^T\right)+\rho u.\nabla u+\nabla p=F \quad (1)$$

$$\nabla . u = 0 \quad (2)$$

B. Conductive and Convective Heat Transfers

$$\rho \frac{\partial u}{\partial t} - \nabla . \eta \left(\nabla u + (\nabla u)^T \right) + \rho u . \nabla u + \nabla p = F \quad (3)$$

TABLE I: PHYSICAL AND TRANSPORT PROPERTIES OF HOT AIR.

	Air
Density (kg/m^3)	1.051
Dynamic viscosity (Pa.s)	199.88×10^{-7}

TABLE II: PHYSICAL AND HEAT TRANSPORT PROPERTIES OF BIO-COALS.

	Coal	Corncob-Coal				Sawdust-Coal				Grounded coffee-Coal				Air
		75-10-15	65-20-15	55-30-15	45-40-15	75-10-15	65-20-15	55-30-15	45-40-15	75-10-15	65-20-15	55-30-15	45-40-15	
Thermal conductivity (W/m.K)	1.323	1.187	1.052	0.916	0.78	1.186	1.048	0.911	0.773	1.191	1.059	0.926	0.794	0.02853
Density (kg / m^3)	1294	1222.5	1151	1079	1008	1181	1067	953	840	1293	1291	1289	1288	1.051
Heact capacity (J / kg.K)	1801	1763	1725	1687	1649	1753	1705	1657	1609	1788	1776	1763	1751	1008.3
Initial Temperature (K)	300.23	300.23	300.23	300.23	300.23	300.23	300.23	300.23	300.23	300.23	300.23	300.23	300.23	333.15

TABLE III: PHYSICAL AND MASS TRANSPORT AND MASS TRANSPORT PROPERTIES OF BIO-COALS.

	Coal	Corncob-Coal				Sawdust-Coal				Grounded coffee-Coal				Air
		75-10-15	65-20-15	55-30-15	45-40-15	75-10-15	65-20-15	55-30-15	45-40-15	75-10-15	65-20-15	55-30-15	45-40-15	
Diffusion coefficient (m^2 / s)	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_1 \times (T/T_1)$	$D_2 \times (T/T_2)$
Initial Concentration (mol / m^3)	8056	7920	7785	7653	7517	9813	11573	13333	15090	9948	11840	13729	15625	2.723
Porosity	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.366	0.335	0.302	0.268	1
Permeability (m2)	1×10^{-18}	1.2×10^{-14}	2.3×10^{-14}	3.5×10^{-14}	4.7×10^{-14}	1.2×10^{-14}	2.3×10^{-14}	3.5×10^{-14}	4.7×10^{-14}	2.34×10^{-12}	4.49×10^{-12}	6.8×10^{-12}	9.16×10^{-12}	1

C. Diffusive and Convective Mass Transfers

$$\rho \frac{\partial u}{\partial t} - \nabla . \eta \left(\nabla u + (\nabla u)^T \right) + \rho u . \nabla u + \nabla p = F \quad (4)$$

D. Applied Boundary Conditions

TABLE IV: MOMENTUM, THERMAL AND CONCENTRATION BOUNDARY CONDITIONS.

Boundary condition	Temperature (K)	Concentration (mol / m^3)	Velocity (m/s)
Left	333.15	2.723	0.04
Right	333.15	2.723	0.05
Top	convective flux	convective flux	Pressure (Pa) 0.028
Down	333.15	2.723	Pressure (Pa) 0.0305
Front	333.15	2.723	Pressure (Pa) 0.03
Back	333.15	2.723	Pressure (Pa) 0.03
Particle Surface	continuity	continuity	continuity

IV. RESULTS AND DISCUSSIONS

A. Flow Structure and Temperature Distribution

The shapes of briquette strongly affected the flow patterns of the hot air around the briquettes, as shown in Fig. 2 at t = 600 sec (Fo = 31.68), which in turn influenced the related heat and mass transfers (moisture removal). The direction of the incoming air was from both sides i.e., identified as left and right sides in Fig. 1(b), and due to the location of installed blowers the flow was quite symmetric with respect to the briquette. The evident hot air plume was a result of the momentum efflux of hot air mainly flowing through the top surface and the buoyancy-driven natural convection stream by the density difference originating from the temperature gradient of hot air about the briquette.

The briquette shapes with sharp corner i.e., cylinder and cubic had a steep temperature gradient and heat transfer rate was higher in that vicinity. On another hand, the temperature profiles of the soap-like and spherical shapes gradually varied.

Since the soap-like shape provided the proper temperature distribution and also a practical ability to handle and storage, the details of curing of this briquette shape was conducted. Fig. 3 provided the history of temperature distribution. The temperature variation within the briquette was caused by the convection heat transfer from hot surrounding air to the briquette surface and the conduction within the briquette. The temperature at the bottom of soap-like briquette rose faster than the upper part by means of heat conduction. The temperature of top portion, however, increased by a slower rate by convection because of the direction of the hot air plume. At this point, it might be advisable to somehow slower the rate of rising of the air plume to induce a more uniform temperature distribution.

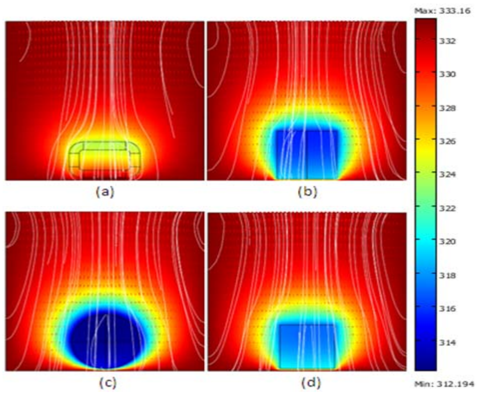


Fig. 2. Streamlines and velocity vectors of hot air about the different shape of coal briquettes superimposed by the temperature distribution (color shading) of hot air and within the coal briquettes: (a) soap-like, (b) cylindrical (c) spherical (d) cubical. All at t = 600 sec (Fo = 31.68)

B. Effects of Briquette Shape

To gain more insight of the performance of curing process, the temperature and concentration as functions of time were determined and shown in Fig. 4. In general, the decreasing rate of moisture concentration for each shape was very well agreed with the trend of temperature variation i.e., the soap-like briquette with the highest temperature increasing rate revealed the highest rate of moisture decreasing but for the spherical briquette the opposite was true.

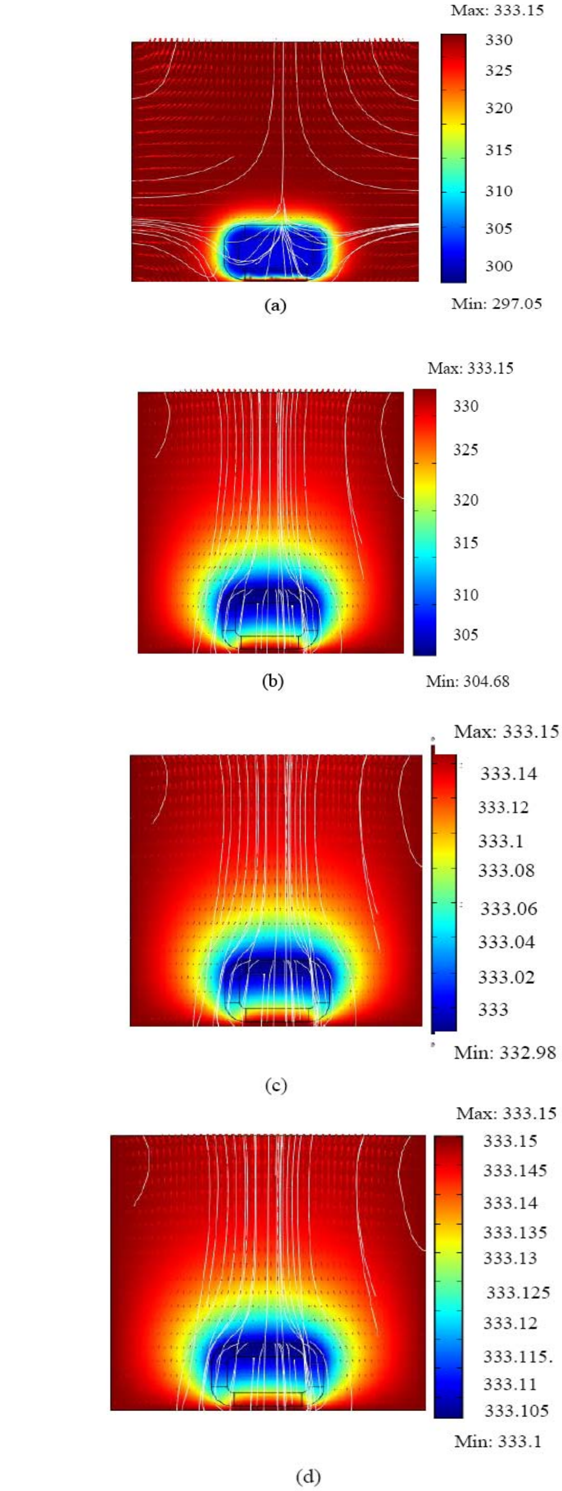
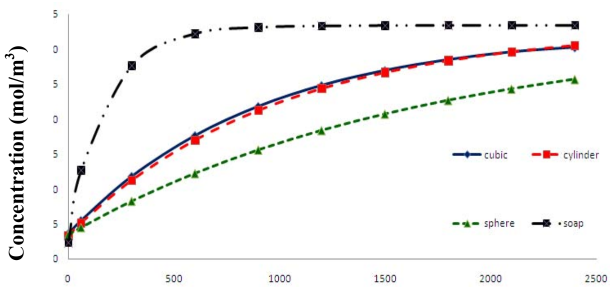


Fig. 3. Transient streamlines and velocity vectors of hot air about the different shape of coal briquettes superimposed by the temperature distribution (color shading) of hot air and within the coal briquettes at: t = 0,60,1200 and1800 sec (Fo = (a) 0 (b) 3.16 (c) 63.37 and (d) 95.05, respectively)



(a)

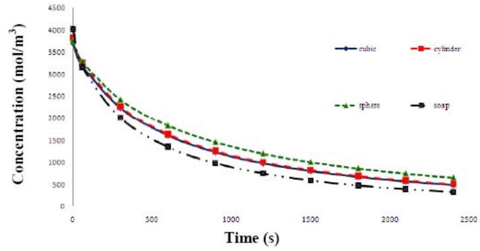


Fig. 4. The average temperature and moisture concentration within coal briquettes of each shape.

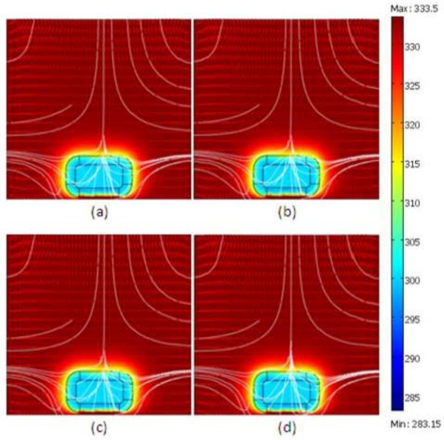


Fig. 5. Initial (0 sec.) temperature distribution of hot air surrounding and within bio-coal briquettes with different and various compositions of coal-biomass-binder: (a) 85-0-15 (b) 65-20-15 corncob coal (c) 55-30-15 sawdust (d) 65-20-15 ground coffee coal

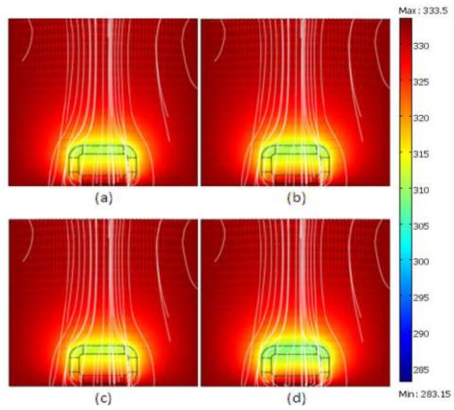


Fig. 6. Temperature distribution of hot air at 120 sec. surrounding and within bio-coal briquettes with different and various compositions of coal-biomass-binder: (a) 85-0-15 (b) 65-20-15 corncob coal (c) 55-30-15 sawdust (d) 65-20-15 ground coffee coal.

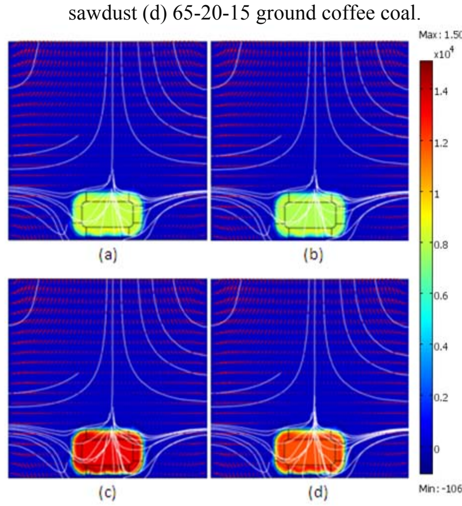


Fig. 7. Initial (0 sec.) concentration distribution of hot air surrounding and within bio-coal briquettes with different and various compositions of coal-biomass-binder: (a) 85-0-15 (b) 65-20-15 corncob coal (c) 55-30-15 sawdust (d) 65-20-15 ground coffee coal.

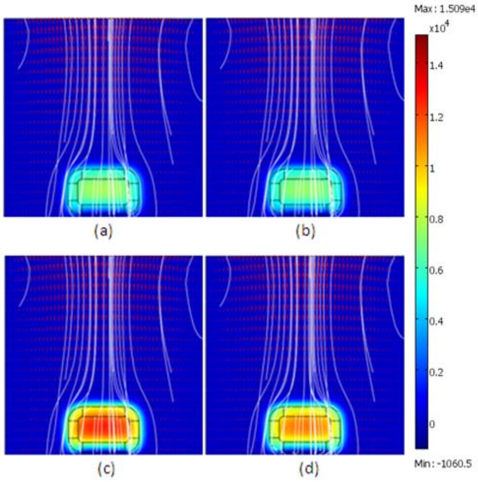


Fig. 8. Concentration distribution of hot air at 120 sec. surrounding and within bio-coal briquettes with different and various compositions of coal-biomass-binder: (a) 85-0-15 (b) 65-20-15 corncob coal (c) 55-30-15 sawdust (d) 65-20-15 ground coffee coal.

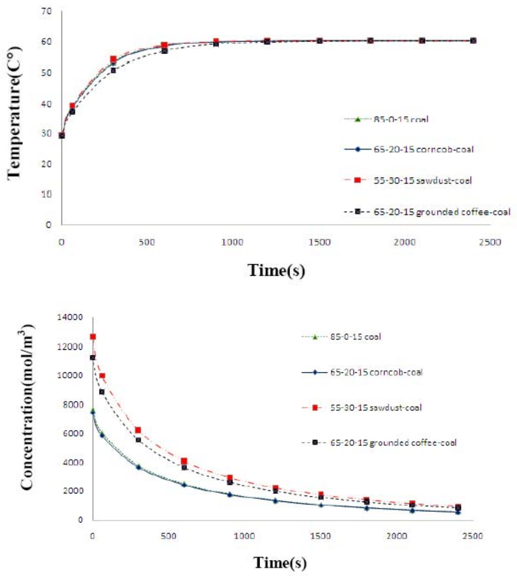


Fig. 9. The average temperature and moisture concentration within coal and bio-coal briquettes with different type of biomass in various compositions of coal-biomass-binder

C. *Effects of Biomass-to-Coal Ratio*

For comparison, the only soap-like shape but different type of biomass was adopted under this topic of investigation. The amount of binder was fixed at 15% by weight for all type of bio-coal briquette, and 85-0-15 meant the briquette had coal 85% by weight, none bio-mass, and binder 15% by weight, for example.

The coupled heat transfer and moisture removal with the bio-coal briquette cause a buoyancy effect surrounding the briquette qualitatively similar to that of the coal briquette. The apparent physical and transport properties of the bio-coal are the major factors lead to the difference in numerical value of the hydrodynamics, thermal and concentration parameters of the curing process. Fig. 5 to 8 illustrated the temperature and concentration distribution at the initial condition and at t = 120 sec after the beginning of the curing process.

The time variations of average temperature and moisture concentration for coal and bio-coal as previously demonstrated in Fig. 5 to 8 were plotted and shown in Fig. 9, whereas the detailed concentration profiles within the coal and bio-coal (Coal-Sawdust-Binder (75-10-15)) briquette were presented in Fig. 10. From Fig. 10, the inner most moisture decreased with the slowest rate since it had to overcome the Knudsen diffusion within coal porosity prior to the convection at the surface by hot air.

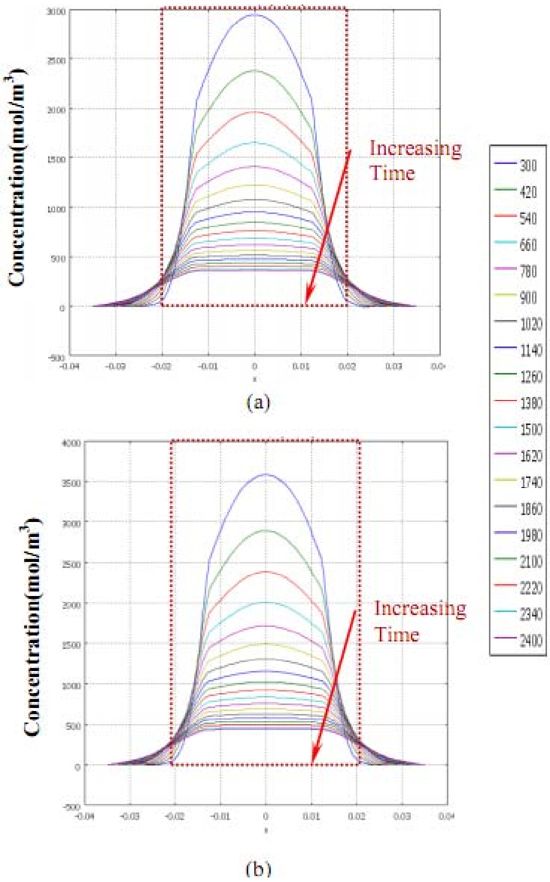


Fig. 10. Comparison of the concentration profiles between (a) the coal briquette and (b) the bio-coal briquette (Coal-Sawdust-Binder (75-10-15)) for the soap-like shape at various times (sec). Dashed-line represents the boundary of briquette

V. Conclusion

It is evident from the simulation results that the shape of briquette, and type and composition of biomass used in bio-coal briquette played a vital role in moisture removal during the curing process. In general, the temperature and concentration variation for all the briquettes reveal similar trends except for the rates. The soap-like shape was considered to be proper for producing the briquette due to its rather uniform distributions and especially the moisture removal rates. The effect of type and ratio of biomass presented in the briquette was also noticeable through the apparent transport and physical properties.

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