Turbulence Modelling on Fluidized Bed Gasification

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Abstract

Energy generation from carbon-based solid materials, such as coal by a gasification process, increasingly has become an essential research subject, as current energy sources are getting to an end. Waste material management is also of considerable significance to dispose of them sustainably and efficiently from the environment. There is, therefore, the need for an advanced modeling approach to maximize the efficiency of coal-derived synthesis gas, and to optimize process parameters for designing a new gasifier. Hence, a two-dimensional (2-D) gasification system was initially simulated by using commercial code ANSYS FLUENT. Devotalilization and char combustion chemical reactions of the process were modeled by User Defined Functions (UDF) to simulate their chemical kinetics more accurately. Once a mesh independency study was fulfilled, performance evaluation was done, and the energy efficiency of the gasification system was also calculated. Subsequently, model validation has been performed, and RANS based turbulence models were examined to find out the best turbulence modeling approach.

1. Introduction

The solid waste is drastically increasing as a dominant pollution issue all around the world. This waste has been disposed to landfill enormously, and most of them have remained a dangerous waste for the ecology, as well as human health. For instance, roughly 55 million tons of post-consumer solid waste is produced by the Far East, Europe, and the USA [1]. Solid waste decreasing, energy generation and clean-burning gas are the main realities to address the attraction of the process. On the other hand, the process is very complicated to visualize, and to explain scientific concepts of the system, such as solid particles, are the real problem associated with combustion. Complete oxidation is hard for solid fuels, and particulate matter is a real problem. For this reason, it is a necessity to develop a simple, reliable, and accurate model for engineering and scientific calculations. In recent years, high-temperature process phenomena such as pyrolysis, combustion, or gasification, as shown in Figure 1, have gained an increased interest in developing more new models for better use of solid waste with regard to regenerating renewable energy [2].
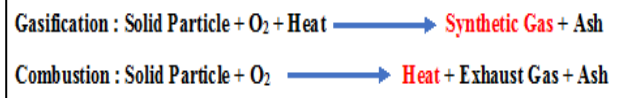
Figure 1. Schematic of chemical reactions for gasification and combustion processes.

Gasification is a gas generation process, which is operated at high temperatures around ($600^{\circ}C$ to $800^{\circ}C$) to react materials without combustion, with a controlled amount of oxygen and/or steam. The process converts organic or fossil fuel-based carbonized materials into carbon monoxide, hydrogen, or carbon dioxide using sequentially occurring chemical reactions, and those output mixture gases are generally called Syngas or Synthetic Natural Gas [3]. Upon generation of the synthetic gas, it is converted to mechanical work, heat, or electricity as a different type of energy for the market demand. Combustion is a thermo-chemical process but produces

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thermal energy without any synthetic gas generation. Pyrolysis is also a similar process like gasification and combustion; it is initially generated bio-oils, and these are finally converted to chemical fuels, like hydrogen. The following literature review is conducted regarding gasification and combustion research.

Gunarathne et al. [4] have studied on pretreatment of biomass, and this method is continuously increasing due to the high demand for it and retaining low energy density. They have used steam-blowed black pellets and unpretreated gray pellets to gasify with air and steam at an updraft high-temperature agent gasification unit. Horton et al. [5] developed a CFD model to simulate a solid waste gasification process using the Fluent commercial code. For this study, the Kinetic Modeling Editor (K.M.E.) was coupled to a Computational Fluid Dynamics (CFD) solver to allow equipment level information into the design. High-temperature air combustion (HiTAC) has been numerically analyzed. HiTAC would be a promising advanced technology for heat regaining, energy-conserving, and stability enhancement of flame. Pour et al. [6] developed a CFD model, which is known as an applied tool to perform (HiTAC) modeling. Zhou et al. [7], worked on steam gasification of municipal solid waste (MSW) using a CaO additive. They used a batch-type fixed bed reactor to investigate the effects of CaO addition on heat transfer properties. Li et al. [8], devolatilized biomass at high temperatures and high heating rates. Biomass reactivity was lowered and allowed greater torrefaction conducted after torrefaction. The kinetic parameters of torrefied biomass were also calculated. CO and H_2 were the primary vaporizing volatiles during the devolatilization of torrefied biomass. The effects of the product yields and composition of the biomass formed during steam pyrolysis were investigated on the metal modified HZSM 5 to the zeolite/binder ratio (Z/B). Catalytic steam pyrolysis of biomass was researched in a bubbling fluidized bed reactor at 450°. The effects of silica-supported transition metals (Ni and V) on product yields and compositions were investigated in [9]. A new solution method for biomass pyrolysis was generated. An advanced 3-D kinetic model was developed for biomass pyrolysis coupled with CFD in this study. Although their simulations were very time consuming, Mellin et al. [10] made it possible to investigate secondary reactions in the biomass pyrolysis. Gunarathne et al. [11] developed an equation for pressure drop divination with a compression influence and presented graphical representations of correlation constants. They also provided a lead to delineate pellet size and designing a grate. Schulze et al. [12] performed a very predictive and novel char particle gasification study to determine the carbon conversion rate for the efficient gasifier. The focus of their research is to develop an alternative advanced model to maximize the efficiency of the gasification process for designing a new gasifier.

Calculation of design variables, optimization of them, stable waste properties, and also determining processing conditions are the second most essential calculations of this study.

As the above literature review illustrates the key features of the gasification process, this research is mainly involved in a set of physical conversions and chemical reactions. It consists of moisture release, devolatilization, tar cracking, and char combustion, as shown in Figure 2.
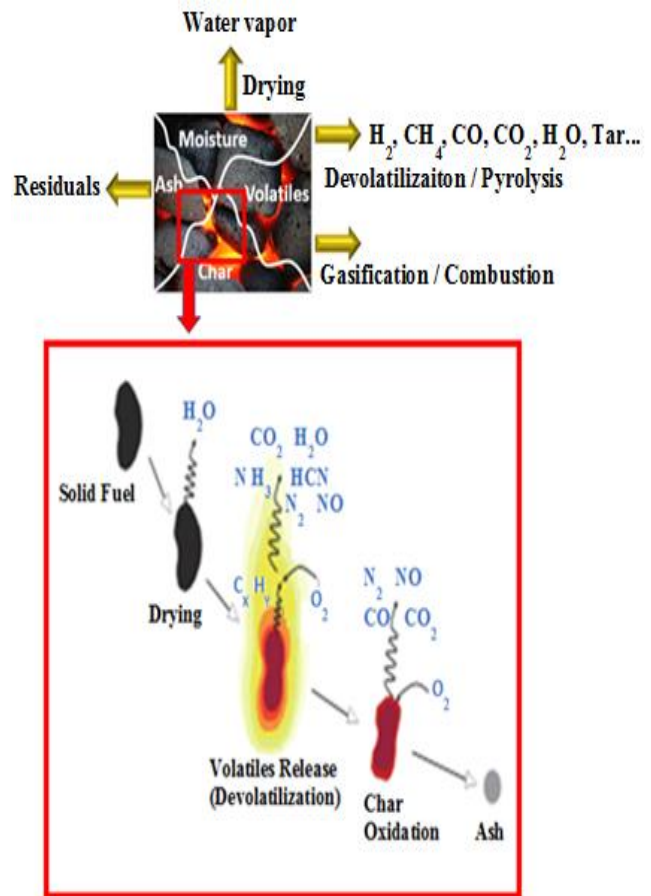

Figure 2. Solid fuel combustion and gasification [13].

As it is mentioned, the gasification is a highly complex thermochemical process, and gasification modeling of solid waste particles is relatively limited in the literature. Hence, in this study, systematic investigation of solid waste as a syngas generation and also understanding the transport phenomena with its chemical reaction mechanisms during the process are of primary interest. The primary purpose of this research is, therefore, to study the gasification of solid waste on particle transport, momentum, heat, and mass transfer. A 2-D multiphase reacting flow model was developed. This developed CFD model may have a significant impact on gasifier design,

process optimization, and it would also be used as a research tool.

2. Materials and Methods

The place of gasifier in the complete set of solid waste gasification and energy generation processes is given in Figure 3. There are different types of gasifiers used for gasification processes such as the Cyclone Gasifier (CG), Downdraft Bioamas Gasifier (DBG), Entrained Flow Gasifier (EFG), and Fluidized Bed Gasifier (FBG), and brief review of biomass gasification modeling can be found in [14].
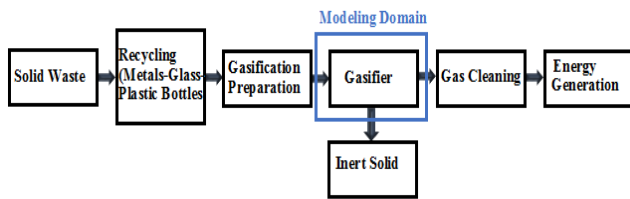

Figure 3. Schematic of solid waste gasification and energy generation.

The main product of the gasification process is the Syngas, i.e., relatively environmentally friendly and energy-efficient gas, which contains carbon monoxide, hydrogen, and methane. The other product is solid leftover, which consists of non-combustible materials (ash) and includes a relatively low level of carbon. Syngas can be used in different ways; for example, Syngas can be burned in a burner to generate steam, which may be used for power generation or industrial heating. It can also be used as a fuel in a dedicated gas engine.

Fluidized bed reactors are used for solid to gas conversion processes thanks to their ability to furnish a high degree of gas-solid contact, fast solid-solid mixing, and fast gas mixing inside of the bed-zone owing to solids-induced flow. Further, fluidized bed biomass gasification is a promising technology for biomass gasification due to its compatibility with the physical and chemical properties of biomass, such as the high grinding cost and low energy density, which makes the adoption of entrained-flow gasification technology techno-economically impractical, as mentioned in [15].

Modeling of the gasification process pertains to the progress of volatile gasification homogeneous chemistry occurring in the gas phase and char particle combustion occurring in the Solid Phase as heterogeneous reactions. Thermodynamic equilibrium(i), kinetic (ii), and artificial neural network routes (iii) are the basic approaches for mathematical modeling of the gasification process as in [14]. Equilibrium or kinetic models, or a

combination of both have their advantages and disadvantages. Whereas equilibrium models are more straightforward in the formulation but do not yield satisfactory results for intricate reactor designs, the kinetic models are complicated in a formulation. Still, their predictions are more accurate compared to equilibrium models for sophisticated reactor designs. Variously, Computational Fluid Dynamics (CFD) fulfills as a tool to examine the behavior of a given gasifier design by combining the advantages of both models [14]. Therefore, in this study, the gasification process inside Fluidized Bed Gasifier is modeled by CFD. A systematic description of the gasification processes inside the fluidized bed gasifier and temperature rises of both coal and air are given in Figure 4.
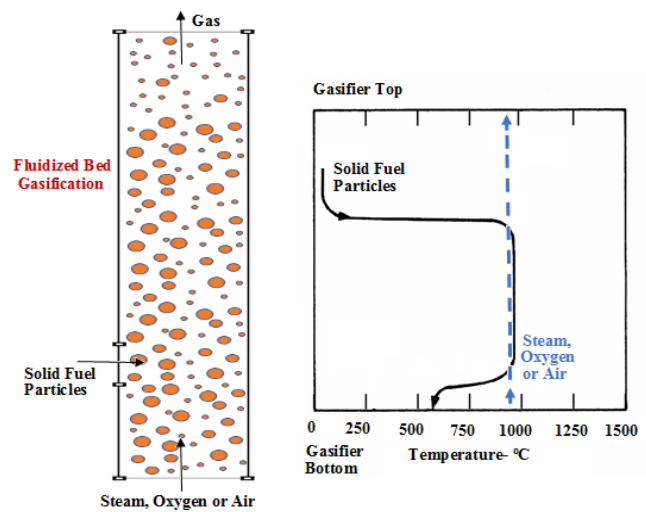
Figure 4. Fluidized bed gasifier [13].

As shown in Figure 4, this 2-D geometry is considered to simulate the gasification of solid waste particles, demonstrating the case set up for Eulerian-granular flow with the heterogeneous and homogeneous reactions. The gas and solid waste particles simultaneously enter the domain from different inlet sides of the geometry. In this case, both primary and secondary phases are modeled, considering as mixture. The primary phase is a gaseous mixture consisting of O_2, N_2, CO, CO_2, tar, and H_2O. In contrast, the secondary phase is a solid waste mixture of C(s), volatiles, $H_2O(l)$, and ash-coal, and initially contains 2% char and 2% volatiles. In this simulation, there are only two heterogeneous and one homogeneous reactions considered. Heterogeneous reactions are for devolatilization and char combustion reaction, whereas the homogeneous reaction is carbon monoxide converting to carbon-di-oxide [13]. The flowchart of the developed CFD model is shown in Figure 5.
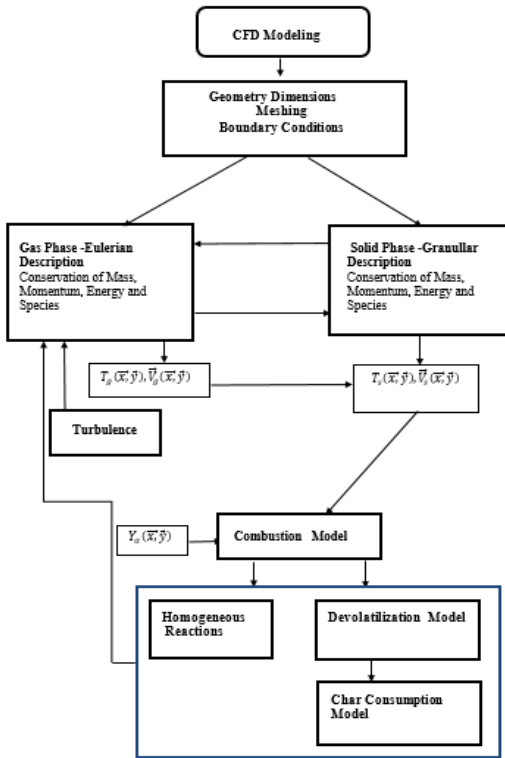
Figure 5. The flowchart of the developed CFD model.

2.1. Computational Domain and Boundary Conditions

Figure 4 is investigated by developing a 2-D planar CFD model, as shown below in Figure 6. Boundary conditions are chosen as velocity inlets (A: Inlet Solid Particules V=0.2 m/s, T=300 K and B: Inlet Gas V=3 m/s, and T=1200 K). Pressure outlet is chosen as Outlet Boundary (C: Outlet Gauge Pressure = 0 Pa), as shown in Figure 6. All other walls are considered as no-slip boundary conditions. They were modeled as an insulated wall. Heat condiction on gasifier walls was not taken into account. Convection and radiation heat transfer from gasifier walls to the environment were also neglected. The

the initial diameter of the solid particle was chosen as 0.0005m, the particle density value is 1400 kg/m3, the specific heat value of the particle is equal to 2092 J/kg K, and the thermal conductivity value of the particle is 1.5 W/mK.
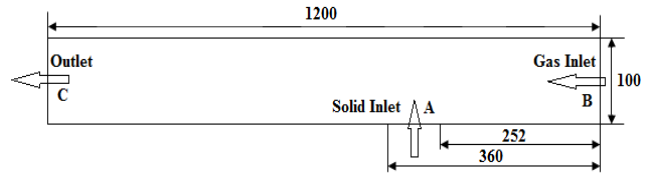

Figure 6. Geometry and dimensions (Dimensions are in mm).

2.2. Grid Independence Study and Mesh Structure

A grid independence study is required to obtain accurate results for all CFD analyses. Mesh is built by using triangular and prism cells of uniform grid spacing, as seen from Figure 7. Fine and uniform grid spacing was used for boundary layer meshes in the vicinity of the walls to effectively capture the hydrodynamics of fluidized bed reactors.
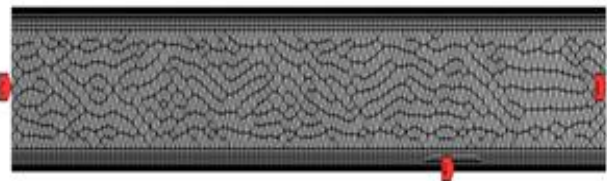

Figure 7. The grid structure of the CFD model.

Grid independency study is initially done by comparing various cell numbers with Maximum Phase 1 velocity changes, as seen below Figure 8; upon completion of this mesh independent study, 99424 elements are decided to be appropriate for accurate data resolution, as well as simulation time-consuming.
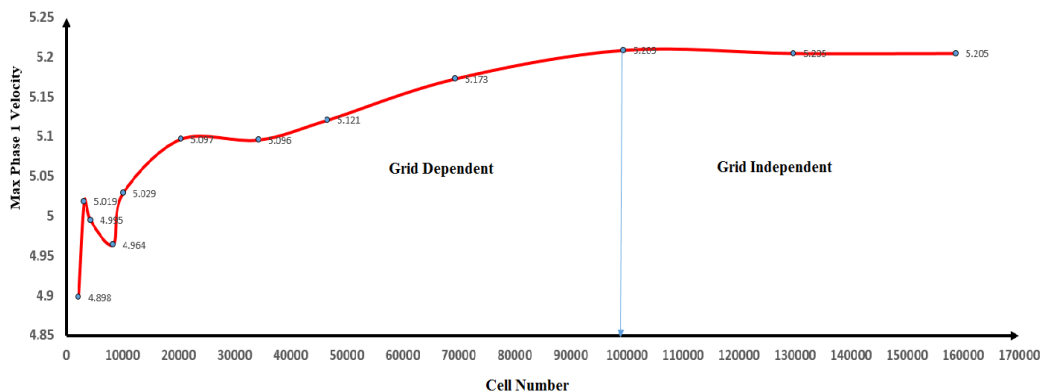

Figure 8. Maximum phase 1 velocity variation with cell number.

2.3. Turbulence Model

Turbulence modeling methods today can be grouped into the following three categories: Reynolds-Averaged Navier-Stokes (RANS) equations, Large Eddy Simulation (LES), and Direct Numerical Simulation (DNS) [16]. Although LES and DNS models are more accurate models than RANS ones, they were not used due to their high costly computing resources for industrial flow applications. RANS based standard k-ε turbulence model is generally used in the modeling of the turbulent flow for combustion and gasification processes in fluidized beds [17]. In this study, various RANS based turbulence models are investigated for determining the most suitable turbulence modeling to obtain reliable calculations of the dependent variable distribution, and several RANS based turbulence models are utilized in order to compare their consistency with the case. For the multiphase turbulence model, the dispersed option was chosen, and computations were performed by using ANSYS-FLUENT.

2.4. Multiphase Reactive Flow Modelling

The Eulerian-Granular modeling approach is used modeling multiphase reactive flow. This model is the most complex, accurate, and state-of-the-art computational technique to analyze multiphase flows in ANSYS FLUENT [18]. This model solves a set of conservation equations for mass species Eq. (1) and Eq. (4), for momentum transport, Eq. (2) and Eq. (5), and for energy transport Eq. (3) and Eq. (6). Those equations were solved for each primary and secondary phase along with the equation of granular temperature, developing the 2-D CFD model, as seen in Figure 9. Phases are coupled via the pressure and interphase exchange coefficients. This coupling approach is handled depends on the type of phases involved. The properties of Granular flow were obtained from the application of the kinetic theory.
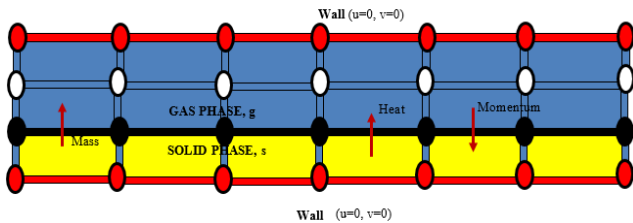
Figure 9. Scheme of CFD model, 2-D steady-state finite volume model.

-Gas Phase:
The species mass equation of gas phase;

$$\nabla.\left(\alpha_g\rho_g Y_i\vec{v}_g\right)=\dot{m}_i+S_i \tag{1}$$

The momentum equation of gas phase;

$$\nabla.\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right)=-\alpha_g\nabla p+\nabla.\overline{\overline{\tau}}_g+\alpha_g\rho_g\vec{g}+K_{sg}\left(\vec{v}_s-\vec{v}_g\right)+\dot{m}_{sg}\vec{v}_{sg} \tag{2}$$

The energy equation of gas phase;

$$\nabla.\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right)=\overline{\overline{\tau}}_g:\nabla\vec{v}_g+\nabla.\vec{q}_g+S_g+Q_{sg}+\dot{m}_{sg}H_{sg} \tag{3}$$

-Solid Phase:
The species mass equation of solid phase;

$$\nabla.\left(\alpha_s\rho_s Y_i\vec{v}_s\right)=\dot{m}_j+S_j \tag{4}$$

The momentum equation of the solid phase;

$$\nabla.\left(\alpha_s\rho_s\vec{v}_s\vec{v}_s\right)=-\nabla p_s+\nabla.\overline{\overline{\tau}}_s+\alpha_s\rho_s\vec{g}+\dot{m}_{sg}\vec{v}_{sg} \tag{5}$$

The energy equation of the solid phase;

$$\nabla.\left(\alpha_s\rho_s\vec{v}_s H_s\right)=\overline{\overline{\tau}}_s:\nabla\vec{v}_g+\nabla.\vec{q}_s+S_s+Q_{sg}+\dot{m}_{sg}H_{sg} \tag{6}$$

Mass, momentum, and energy Interphase exchange between these phases is dependent upon the type of mixture being modeled, as shown in Figure 10, mass, momentum, and heat transport at the interface. Interface transport equations, Eq. (7), Eq. (8), Eq. (9) were solved:
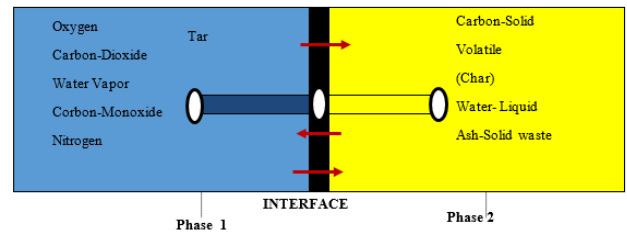
Figure 10. Material mixtures, mixture gas (phase 1) & mixture solid (phase 2).

$$m_p C_p \frac{dT_p}{dt}=hA_p\left(T_\infty-T_p\right)+\frac{dm_p}{dt}h_{sg}+S_x \tag{7}$$

$$-Q_{sg}=Q_{sg}=\frac{6K_g\alpha_s\alpha_g Nu_s}{L_s^2}\left(T_s-T_g\right) \tag{8}$$

Nusselt number is correlated by Gunn [19];

$$Nu_s=(7-10\alpha_g+10\alpha_g^2)(1+0.7Re_s^{0.2}Pr_g^{0.33})+ \\ (1.33-2.4\alpha_g+1.2\alpha_g^2)Re_s^{0.7}Pr_g^{0.33} \tag{9}$$

2.5. Modelling Chemical Reactions and Species Modelling

Chemical reactions are modeled by using a volumetric reaction in Species Transport, while the Finite-Rate/Eddy Dissipation Model is used for Turbulence and Chemistry Interaction. Species transport Eq. (10) is solved, and the convection-diffusion equation is used to compute the mass fraction of each specie Y;

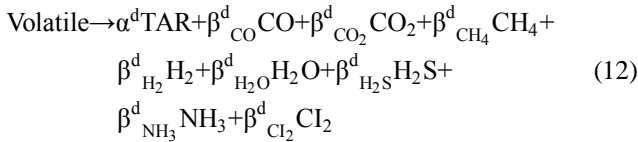$$\frac{\partial(\rho Y_j)}{\partial t}+\nabla.(\rho Y_i V)=-\nabla.J_i+R_i+S_i \tag{10}$$

For the realistic coal combustion or gasification process, it is necessary to consider more heterogeneous and homogeneous reactions. Two heterogeneous reactions are considered, one for char combustion and the other for devolatilization, and three reactions are only used for this study.

Chemical reactions of the gasification process are as follows;
a-) Char Combustion, Heteregenous Reaction, as formulated in Eq. (11);

$$2C<S>+O_2 \rightarrow 2CO \tag{11}$$

b-) Devolatilization, Heterogeneous Reaction, as shown in Eq. (12);

$$Volatile \rightarrow \alpha^d TAR+\beta^d_{CO}CO+\beta^d_{CO_2}CO_2+\beta^d_{CH_4}CH_4+$$
$$\beta^d_{H_2}H_2+\beta^d_{H_2O}H_2O+\beta^d_{H_2S}H_2S+ \tag{12}$$
$$\beta^d_{NH_3}NH_3+\beta^d_{CI_2}CI_2$$

c-) CO combustion, homogeneous reaction;

$$CO+0.5O_2 \rightarrow CO_2 \tag{13}$$

Along with more reactions, the efficiency of the gasification process would be higher, and much more accurate, as well as gasification process simulation, would be much closer to real gasification. Gasification process should also be optimized by means of the size of the feeding material particles, the shape of the particles, the structure of the material (porous, non-porous), environment (reactive Air/Oxygen, Inert Nitrogen/Argon), flow of the medium, heating rate (slow-fast), Temperature (Low $<500^oC$, High $>500^oC$).

Radiation calculation should also be considered to get a more accurate temperature distribution on the gasifier domain. This work only demonstrates the use of multiphase flow along with chemical reactions, without considering radiation.

2.6. Model Validation

This CFD model is validated by Liu's work [20], as seen in Figure 11, and Solid Volume Fraction was compared, as shown in Figure 12 and Figure 13. The agreement between the present numerical results and Lui's results is quite similar. For model validation, another asymmetric model was prepared exactly the same as Lui's study, including the same 2-D dimensions with similar boundary conditions in order to compare both models' results. Lui's findings, which is time-averaged solid volume fraction, were compared with solid volume fraction distribution of this present study. As shown in Figure 13, a point value comparison was fulfilled. The maximum solid volume fraction was 0.565; on the other hand, Lui's maximum solid volume fraction value was 0,559. Error percentage was also very low as %1.07 when comparing both models.
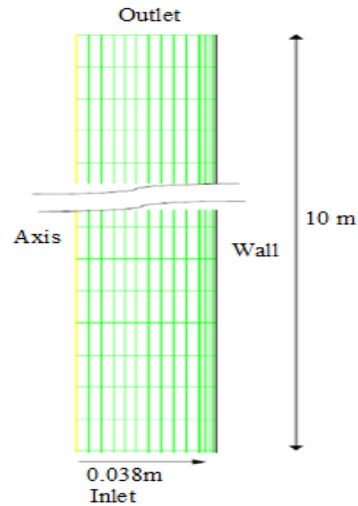

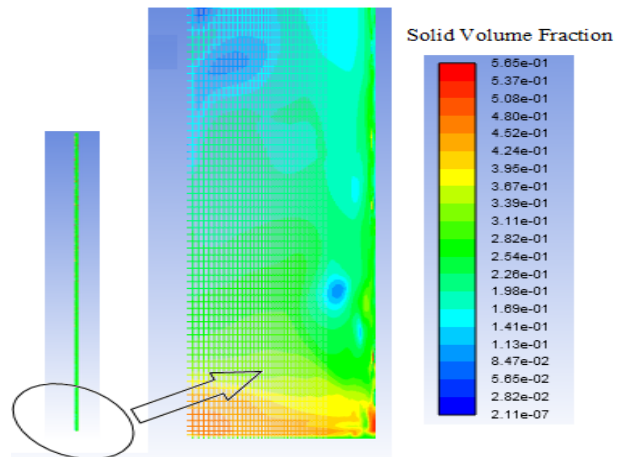**Figure 11.** Geometry dimensions, mesh structure, and boundary conditions of the Hui Liu Model [20].

Figure 12. Solid volume fraction distribution contour results of the present study.

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2.7. Numerical Procedure

The gasification process is analyzed by using commercial software ANSYS-FLUENT, which is a finite volume method based CFD pressure solver. Pressure based solver was used. The gravity force was taken into account. Moreover, viscous heating was neglected for this calculation. The phase-couple SIMPLE scheme is used for solving the pressure–velocity coupling. The cell center method was used. The mesh was generated by using triangle cells with uniform grid spacing. The second-order upwind scheme was used to discretize the convective terms in the momentum, mass, and energy equations. The gas-solid multiphase flow was previously solved without using energy equations and chemical reactions to find a stable solution. The chemical reactions and heat transfer modes were included, and the full reactive flow system was solved after finding a sufficient flow pattern. The convergence criterion was 10e-6 for residuals of the continuity and momentum equations and 10e-10 for residual energy equation. k-ε Standart turbulence model and standard wall function were used for calculations.

3. Results and Discussion

After the full non-linear coupled partial differential equations are solved by this developed CFD model, results were visualized by colorful contours, initially as seen in Figure 13, which shows a molar concentration of CO distribution in the domain. Carbon monoxide is the main product of the gasification process. Therefore, it is initially critical to analyze the amount of CO. It also shows efficient gasification locations.
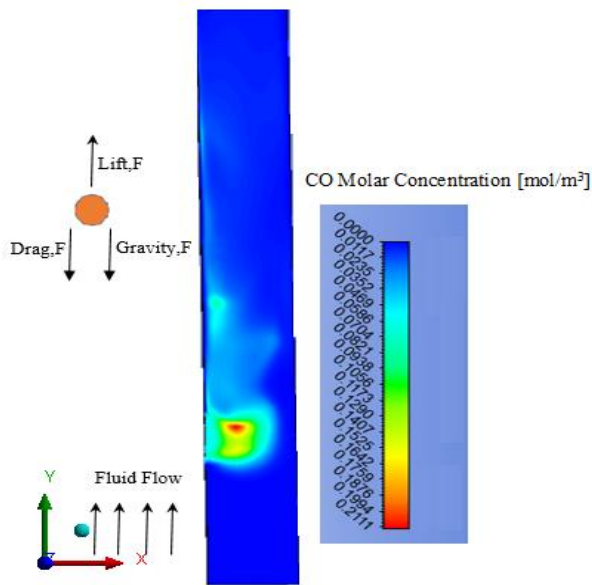
Numerous parameters can be calculated by this developed CFD model, like dynamic viscosity, species concentration, pressure, velocity, and temperature distributions of this mixture flow, and they can be investigated, which are the important reactive flow properties. For instance, velocity distribution can be analyzed for both phase 1 and phase 2, as seen in Figure 14. Particle pathlines and gas streamlines were prepared together in Figure 14. It does show particle behaviors in the hot gas flow, and it is critical to visualize both particle pathlines and gas streamlines in terms of proper gas-solid mixing and more efficient gasification or combustion.

Figure 15 shows the turbulence kinetic energy and velocity relations. Turbulence kinetic energy is higher where the chemical reactions have occurred, and phase velocities are getting higher when to combine phase 1 and phase 2. Turbulence kinetic energy indicates turbulence intensity occurring in the flow, and it can visualize higher turbulence locations in the flow domain. Velocity distribution is also critical for design gasifier. Min velocity values close to zero shows dead areas in the flow domain, and Max velocity values show, especially particle higher velocities, can cause damage on gasifier walls. By the way, homogenous distribution velocity means homogenous gas and solid mixing. Proper mixing does increase the efficiency of gasification or combustion processes. When turbulence kinetic energy increases, gasification efficiency would increase, and the right mixing conditions would have occurred.
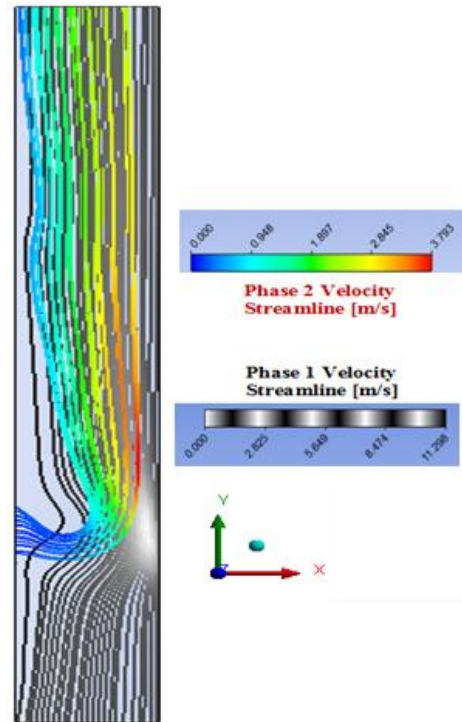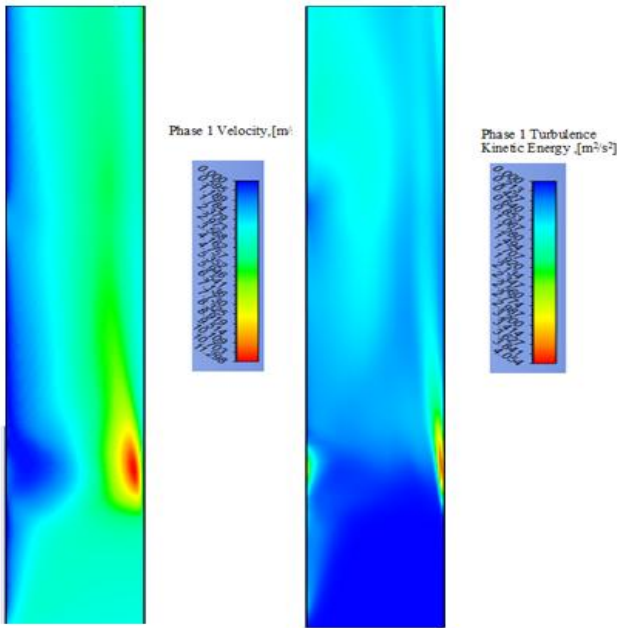

Figure 13. The molar concentration of CO for phase 1.

Figure 14. Phase 1 and phase 2, velocity streamlines.

Figure 15. Phase 1 Turbulence kinetic energy and velocity distribution.

Calculations of energy efficiency and gasification performance were calculated following Eq. (15) and Eq. (17) by using Eq. (14) and Eq. (16).

Cold gas efficiency;

$$\eta_m = \frac{H_g\,Q_g}{H_s\,M_s}\,x100 \tag{14}$$

$$\eta_m = \frac{15000\frac{kJ}{m^3}\times 3.385786\ m^3/sn}{13400\frac{kJ}{kg}\times 6.4067\ kg/sn}\,x100 \ \Rightarrow\ \eta_m = \%\ \mathbf{59} \tag{15}$$

Hot gas efficiency;

$$\eta_m = \left(\frac{H_g\,Q_g + Q_g\,\rho C_p(t_g - t_a)}{H_s\,M_s}\right)x100 \tag{16}$$

where $H_{sensible} = C_P\,Q_g\,\rho(t_g - t_a)$

$$\eta_m = \frac{15000\times 3.385786 + 6200kJ/sn}{13400\frac{kJ}{kg}\times 6.4067\ kg/sn}\,x100 \ \Rightarrow\ \eta_m = \%\ \mathbf{66} \tag{17}$$

Gasification efficiency is an important factor in determining parameters of constructing a gasifier in terms of economic feasibility. For thermal applications, if synthetic gas is not cooled before the combustion process, the efficiency of gasification is formulated as the addition of sensible heat of the gas, as shown in the above correlations.

Cold gas efficiency as 59% and hot gas efficiency as 66% obtained were normalized values, comparing to the highest efficiency. The gasifier efficiency would be

increased more with the process and design parameters optimization.

This work can be compared with Couto et al.'s study [21], as seen in the following results in Figure 16, although Couto et al.'s research and this present study are modeled with different domain size and using different boundary conditions [21]. Contours of CO_2 mole fractions were compared. Carbon monoxide is also a combustible product of the gasification process. It is good to calculate the amount of CO_2 and visualize CO_2 distribution in the flow domain.
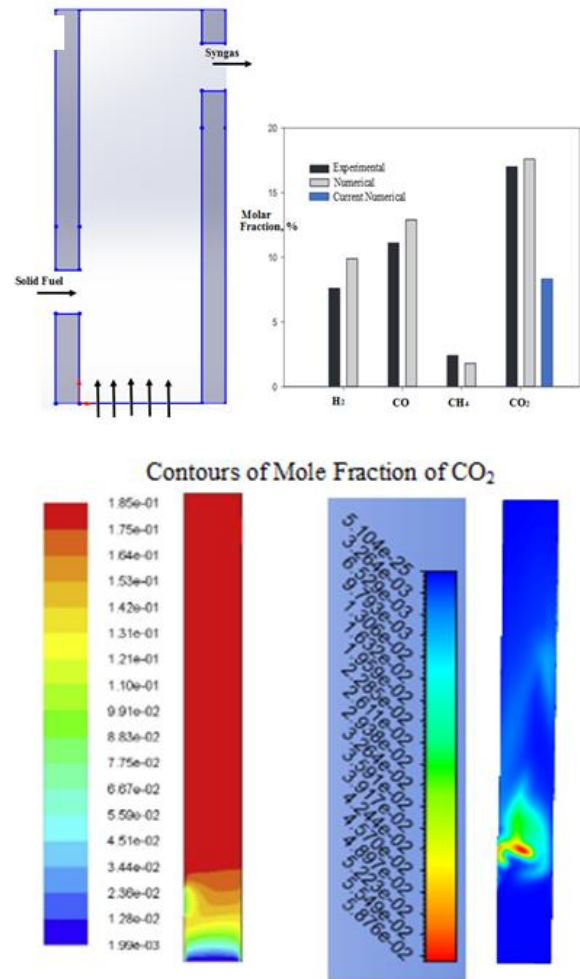
Figure 16. Mole fraction comparison of present results with experimental and numerical results of Couto et al. [21].

In addition to those above findings and explanations, gasification performance is evaluated in terms of the particle size diameter. For some calculations, syngas efficiency is increased when the diameter of the solid particle is decreased. For instance, when the particle diameter was 0.00050 m, syngas flow rate 0.121 kg/s when the diameter was reduced to 0.00001 m, the syngas flow rate was getting an increase to 0.0125 kg/sn.

Solid particle diameter was tried to optimize as one of the essential process parameters. For the gasifier design, turbulence modeling was carefully researched for gasification performance and syngas quality. As shown below, Tables (1-4) results of RANS based commonly used turbulence models are initially compared with each other for various wall functions. A double mesh structure was used to compare turbulence models. Mesh structure was changed to make y plus value around 1.5 when to use all enhanced wall treatments. Y plus value was around 4 for all other wall functions.

Reynolds stress turbulence model with enhanced wall treatment, as seen in Table 1, has correctly calculated Solid Volume Fraction and phase1 velocity. On the other hand, the Reynolds stress model with standard wall function has calculated the solid volume fraction very accurately (0.5959424); however, phase 1 velocity value was not accurate (18.85557m/s) as much as generated previously with enhanced wall treatment. The cell height next to the wall should be coarsened when using this standard wall function. Y plus value should be increased to at least around 30 to get more accurate results for standard wall functions. Overall, Reynolds stress turbulence models are time-consuming and hard to stabilize the numerical scheme when comparing k-ε models.

k-ω Standard, SST, and BSL models were compared, as shown in Table 2. k-w models do not need wall function treatment since they need y+ to be 1. Y plus value was the maximum point value equals 1.5. Results were in acceptable ranges; however, solid volume fraction and phase 1 velocity calculated by those models were little far away from the accurate results. On the other hand, numerical stability and time-consuming factors are satisfactory, comparing to Reynolds stress models.

Table 1. Reynolds stress turbulence model comparison.

RANS based Turbulence Models	Wall Function	Solid Volume Fraction	Phase1 Velocity
Reynolds Stress (5 equation)	Enhanced Wall Treatment	0.629496	11.24822 m/s
Reynolds Stress (5 equations)	Standard Wall Function	0.5959524	18.85557 m/s

RANS are completely different than RSM (Reynolds Stress Models). So it is seen that the results also compared RANS with RSMs. RANS (Reynolds Average Navier Stokes Equations) based turbulence models were compared, as seen Tables (1-4).

Table 2. k-w turbulence model comparison.

RANS based Turbulance Models	Wall Function	Solid Volume Fraction	Phase 1 Velocity
k-ω Model SST	-	0.629496	10.54487 m/s
k-ω Model BSL	-	0.5620949	12.12203 m/s
k-ω Model Standart	-	0.629496	12.99466m/s

Table 3. k-ε standard turbulence models.

RANS based Turbulence Models	Wall Function	Solid Volume Fraction	Phase 1 Velocity
k-ε Model Standard	Menter-Lechner	0.629496	14.50941 m/s
k-ε model Standard	Enhanced Wall Treatment	0.629496	19.85524 m/s
k-ε model Standard	Non-equilibrium Wall Function	0.629496	8.876338 m/s
k-ε model Standard	Scalable Wall Function	0.629496	9.869212 m/s
k-ε model Standard	Standard Wall Function	0.615978	10.77692 m/s

Results are more efficient with k-ε turbulence models when to use standard wall function, and Reynolds stress five equations model with enhanced wall treatment. Standart wall function, which is a near-wall treatment approach, is used when y+ value is greater than 30. When y+ value is equal to 1, two equations k-ε turbulence model with enhanced wall treatment generates more accurate results than others. In addition to the above conclusion, when choosing a reliable turbulence model, higher convergence residual, numerical stability, and fast solving

issues were considered as well. Y plus values were used as 1.5 and 4 for current work, which was the maximum point values of the computational domain.

Table 4. k-ε RNG turbulence model.

RANS based Turbulence Models	Wall Function	Solid Volume Fraction	Phase 1 Velocity
k-ε Model RNG	Menter-Lechner	0.629496	10.62368m/s
k- ε model RNG	Enhanced Wall Treatment	0.629496	11.66239 m/s
k-ε model RNG	Non-equilibrium Wall Function	0.629496	8.876338 m/s
k-ε model RNG	Scalable Wall Function	0.629496	9.93663m/s
k-ε model RNG	Standard Wall Function	0.615978	10.77692 m/s

4. Conclusion

In this 2-D study, the complex gasification process inside fluidized bed gasifier by considering two heterogeneous and one homogeneous reaction were modeled by developing a CFD model.

The standard k-ε model with standard wall function was used in this study since RANS based standard k-ε turbulence model is generally used in the modeling of the turbulent flow for combustion and gasification processes in fluidized beds. The performance of this model was also compared with RSM (Reynolds Stress Model) model and RNG k-ε model with various wall functions to check the suitability of the model. Results were satisfactory by using the Reynolds Stress model with enhanced wall treatment, as mentioned, and highlighted the text with a blue color in Table 1. k-ε model with standard wall function has generated the best proper results among the above turbulence models, as mentioned in Table 3, even if y plus value was around 4. k- ε RNG turbulence model has also generated very similar results with the k-ε model with standard wall function.

Two heterogeneous reactions are considered, one for char combustion and the other for devolatilization, and three reactions are used for this study.

After the full non-linear coupled partial differential equations are solved by developed CFD model, molar concentration of CO, phase 1 and phase 2 velocity streamlines, phase 1 Turbulence kinetic energy and velocity distribution, and contours of mole fraction of CO2 were obtained.

Gasification efficiency is an important factor in determining parameters of constructing a gasifier in terms of economic feasibility. Cold gas efficiency and hot gas efficiency were calculated as 59% and 66%.

This developed CFD model would have a significant impact on gasifier design, process optimization, and it would also be used as a research tool.

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