У попередньому дослідженні було розроблено CFD-моделювання для прогнозування характеристик горіння в котлі з киплячим шаром та пиловугільному котлі. Високий попит на вугілля, що використовується для котлів з механічною топкою на електростанціях Індонезії, створює труднощі через низьку теплову ефективність. В даному дослідженні розглядається CFD-моделювання для прогнозування розподілу температури, теплоти реакції, масової частки CO і CO_2 в котлі з механічною топкою. Геометрія котла моделюється у вигляді камери згоряння до області перед підігрівачем. Граничні умови задаються відповідно до керуючих рівнянь в програмному забезпеченні ANSYS Fluent. Для вивчення впливу спостережуваних значень визначаються параметри вугілля, такі як розмір частинок та властивості вугілля. Задаються чотири моделі для забезпечення комбінації розмірів частинок і властивостей вугілля. Розроблено стратегію вирішення завдання зниження нестабільності процесу моделювання. Моделювання спалювання вугілля включає кілька фізичних процесів, які можуть привести до проблеми чисельної стабільності, коли всі процеси виконуються одночасно. Для запуску рішення моделі були використані три етапи. Формується графік розподілу температури, теплоти реакції, масової частки CO_2 та CO. Максимальна температура в 1-4-ї моделі становить 1440,95, 1473,85, 1347,72 і 1617,17 [K]. Кількість CO, виробленого з кожної моделі, має тенденцію до збільшення; відповідно від 1-ї до 4-ї моделі – 2.314E-07, 5.878E-07, 5.678E-07 і 7.904E-07. На підставі результатів моделювання видно, що розмір часток вугілля впливає на характеристики горіння в вугільному котлі з механічною топкою

Ключові слова: котел з механічною топкою, розподіл температури, теплота реакції, масова частка CO та CO_2

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CFD MODELLING OF PARTICLE SIZE EFFECT ON STOKER COAL-FIRED BOILERS COMBUSTION

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1. Introduction

Stoker-fired boilers had been used for the combustion of coal in the power plant although low thermal efficiency. Higher domestic demand for coal in Indonesia for power generation occurs due to adopted coal as it is inexpensive and readily available [1]. The influence of characteristic zones temperature of coal combustion in a stoker-fired boiler was investigated during the process of drying, degassing, and burn-out on changes in physical and chemical parameters of bituminous coal and slags [2]. In the recent years, computer simulation based on Computational Fluid Dynamics (CFD) had been developed rapidly to provide a reasonable prediction of coal combustion in fluidized bed boilers [3]. The temperature distribution and particle residence time calculated incorporated with operating conditions and coal properties were used for the predictions. The factors affecting Unburn Carbon (UC) levels in ash fall within two major groups, the effect of coal characteristics and the effect of combustion system design and operating conditions [4]. One of the most significant coal characteristics affecting UC content in coal combustion ashes is the particle-size effect [5]. Based on global commitment to a Climate Change Program on the Kyoto Agreement of 1997, it agreed to take actions to reduce the emission of harmful gases to the atmosphere and make quantifiable annual reductions in fuel used. One of the objectives of boiler performance optimization is using the same fuels more efficiently. Several parameters on the boiler performance problems in operating conditions can be predicted more easy and faster than experiment setting and measurement. By using CFD results, preliminary data can be used to obtain optimum conditions on the boiler operation. In this study, CFD analysis for stoker fired boiler on the effect of particle size and properties of coal is investigated.

2. Literature review and problem statement

In a steam power plant system, the boiler function is to produce high-pressure and high-temperature steam. The vapor is expanded inside the turbine to produce mechanical energy as the turbine shaft rotation and then it is used to rotate the generator to produce electricity. The heat energy on the conversion of liquid phase into steam is produced from the combustion process. Gas, liquid, or solid can be used as boiler fuel. Coal is one of solid fuels that is widely used as a source of energy in the boiler. Based on the combustion method, boiler with coal fuel can be divided into the pulverized boiler, fluidized bed boiler and stoker boiler. Fig. 1 shows the different methods of combustion on the three types of boilers.

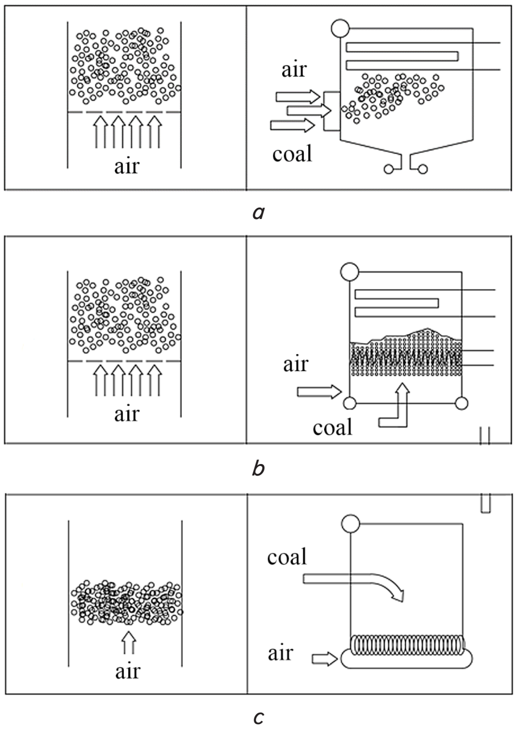

Fig. 1. Boiler Combustion system schematic: *a* — Pulverized boiler; *b* — Fluidized bed boiler; *c* — Stoker boiler [6]

In pulverized boilers, the coal with very fine granules, about 30–40 µm, is injected with the air by using a burner. Coarse grains flow with the air and then burn. The combustion efficiency is very high with a small amount of excess air due to the size of the coal grain is very smooth. Coal grains will be suspended in the hot air flow and the combustion process occurs. The fluidized bed boiler uses coal with larger granules, up to 10 mm. The combustion airflow is lower than the pulverized boiler. Under these conditions, coal grains will be suspended in the flow of hot air and the combustion process occurs. The stoeker boiler uses a larger grain size of coal, up to 30 mm. The combustion airflow is the lowest compared to the previous two combustion methods. Thus, coal burns under static condition; it is not carried by airflow. Coal is placed and burned on the conveyor. The advantage of the stoker boiler combustion is the coal with a large size used, but it requires more excess air and lower burning efficiency.

Indonesia is one of the world's largest producers and exporters of coal. In the January-August 2017 data, 194.215-ton coal was produced in Indonesia [7] and more than 160 billion as mine reserves has been estimated to last around 83 years. The three largest regions of Indonesian coal resources are South Sumatra, South Kalimantan and East Kalimantan. Around 60 % of Indonesia's total coal consists of the lower quality coal and this coal is affordable for Stoker fired boiler energy input. The stoker fired boiler for a power plant under 10 MW is appropriate in the small island and also use in the sugar companies in Indonesia. In the recent years, CFD analysis had been developed to analyze the pulverized and fluidized bed boiler. The accumulation of fine coal particles in beneficiation due to poor screening efficiency and attrition of coal samples was investigated in a coal beneficiation fluidized bed [8]. Study of fine coal accumulation in a CBFB by experimental approach denotes that a proper addition of fine coal particles (in size of 0.45–0.9 mm) in the medium can reduce the bed density effectively [9]. Effect of two types of coal with different characteristics was compared on the degree of fouling in a hot water stoker-fired boiler after it has been fired for an extended period of time [10]. In the previous study of CFD analysis for stoker fired boiler more realistic baseline coal combustion was developed with the heat exchanger models [11]. In the study of numerical modeling techniques, it provides more calculation time and computationally expensive. For this reason, CFD modeling with visualizations and quick predictions become an important work to evaluate different fuel options and its characteristic.

A one-dimensional transient model for a fixed bed was developed to perform computer simulations of straw combustion [12]. The solid phase and gas phase reactions were coupled into a four-step process: evaporation of moisture, volatile release/char formation, burning of the volatiles, and the oxidation of the char particles. Verification was done and the computer models were similar trend with the experimental data. The two-dimensional model was developed by several researchers [13–15].

In the other study on the combustion experiments, the increasing particle size produces the whole burning profile shifted to higher temperatures, and characteristic temperatures are increasing [16]. This confirms that there is a connection between mass transfer effects, and different physical properties of coal particles and the resulting chars due to different particle size. On the other hand, properties of coal as fuel input in the Stoker Boiler in Indonesia tend to vary each time of delivery. Based on these conditions, CFD analysis for stoker fired boiler is developed especially effect of particle size and properties of coal. The study was conducted to address the challenges of operating a power plant with a low-efficiency on Stoker Boiler technology. By using this result, it can be used to predict boiler performance problems in operating conditions. In the other view, the strategies of modeling are required to develop due to the complexitas problem effect on the 3D model to slow and expensive computation solving time. In this study, CFD modelling strategies are provided and used for simulation and quick predictions to evaluate the effect of particle size and properties of coal.

3. The aim and objectives of the study

The study was conducted to address the challenges of operating a power plant with a low-efficiency on Stoker Boiler technology. CFD (Computational Fluid Dynamic) can be used to predict boiler performance problems in operating conditions.

To achieve this aim, the following tasks were set:

– to provide CFD simulation on stoker fired boiler combustion;

– to plot temperature distribution, heat of reaction, CO_2 and CO mass fraction;

– to find the effect of particle size and properties of coal on boiler combustion observed.

4. Materials and methods of research

CFD modeling is generated by using the commercial CFD platform ANSYS-Fluent. Particle size is varying in the max diameter and coal properties are set for two conditions of LHV. Table 1 shows the parameter design used.

Table 1

Coal particle size and LHV coal variable

No	Coal LHV	Coal particle size
Model 1	4,397	0.02 m
Model 2	4,397	0.04 m
Model 3	3,900	0.02 m
Model 4	3,900	0.04 m

Fig. 2 shows the schematic of Stoker coal-fired boiler. The coal burners are assumed to inject the coal from bottom direction. The coal properties are listed in Table 2. The coal size distribution can be shown in Fig. 3 according to the data sampled at the power plant.

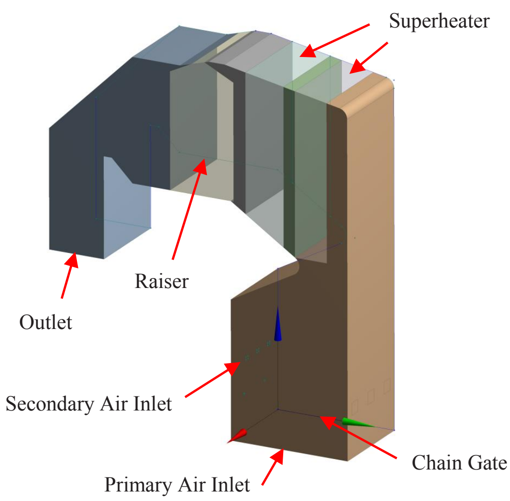

Fig. 2. The Stoker-coal fired boiler schematic as set in the CFD model

Table 2

Coal properties

Proximate analysis (*As-Received*)	
Volatile Matter	34.38 %
Fixed Carbon	29.67 %
Ash Content	3.08 %
Total Moisture	32.87 %
Data Ultimate (Dry Ash Free)	
Carbon	71.20 %
Hydrogen	5.81 %
Nitrogen	3.89 %
Oxygen	19.08 %

Fig. 3. Size distribution of coal data sampled in the power plant

5. Results of the research of particle size effect on stoker coal-fired boilers combustion

Based on the temperature distribution results in Fig. 4, it can be shown that all models have similar trend distributions which difference value of temperature. In the 2–4 meters around chain gate to the vertical direction, model No. 4 with HHV 4937 and coal particle size 0.04 m produce the highest temperature (Fig. 5) with dominant red colour. The lowest temperature occurs on the model No. 1 with 3,900 HHV and coal particle size 0.02.

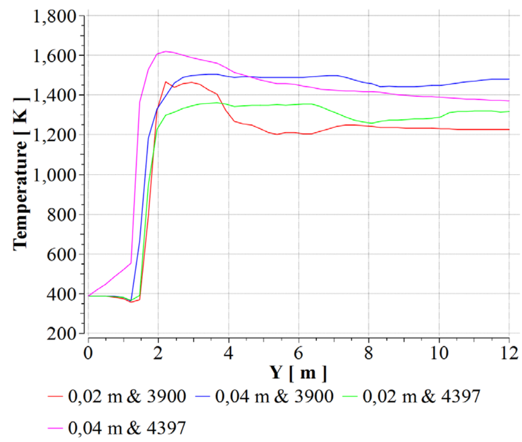

Fig. 4. Temperature distribution of coal particle size and HHV variation

The maximum temperature in the 1^{st} to 4^{th} models is 1440.95, 1473.85, 1347.72 and 1617.17 [K]. Fig. 6 shows the heat of reaction distribution which is the heat generated by complete combustion with a stoichiometric mixture. The model No. 4 shows a heat zone in the upper left area inside the furnace that allows a thermal load to cause damage in this boiler location. Several studies provide the similar condition with these results, compared with HHV values, coal particle size has a more significant effect on the temperature distribution and heat of reaction characteristics.

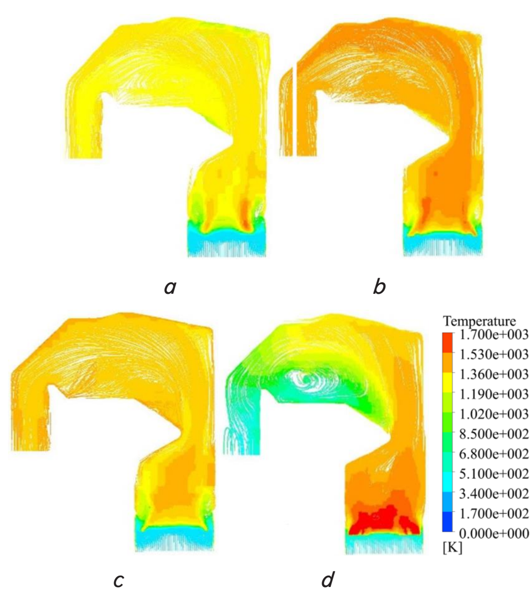

Fig. 5. Temperature distribution of coal particle size and HHV variations: *a* – 0.2 mm & 3,900; *b* – 0.4 mm & 3,900; *c* – 0.2 mm & 4,397; *d* – 0.4 mm & 4,397

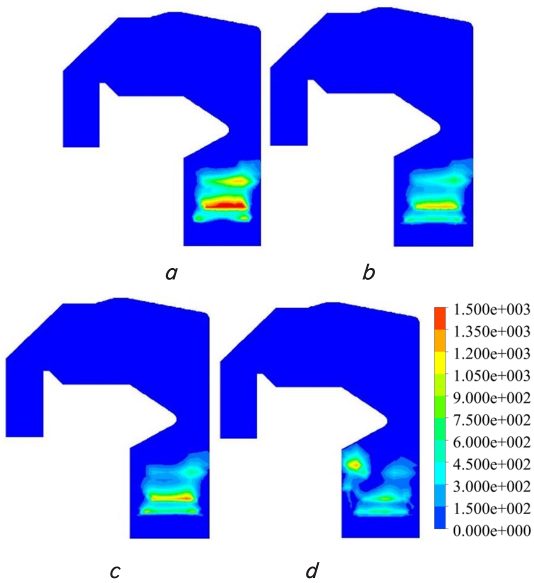

Fig. 6. Heat of reaction distribution for variation of coal particle size and HHV variations: *a* – 0.2 mm & 3,900; *b* – 0.4 mm & 3,900; *c* – 0.2 mm & 4,397; *d* – 0.4 mm & 4,397

6. Discussion of the results of research

In this study, discrete particle model (DPM) was used to model the coal feeding to the combustion chamber [17]. Lagrangian particle in the Eulerian zone is used as a model which coal is injected in terms of parcels. A parcel provides representative classes of identical, non-interacting droplets. The calculation time can be decreased significantly. Coal calculator in ANSYS Fluent can be used to estimate the coal composition and reaction coefficients in the simulation. For this process, the data of proximate and ultimate analysis are required. Two Reaction mechanisms were chosen to provide a plot of combustion mechanisms in the early stages of producing CO and the next stage of producing CO_2.

The momentum and mass transfer were solved assuming a compressible gas mixture. An Equation-Of-State (EOS) is required to couple density, pressure and temperature, and in this study the Ideal Gas Equation was selected. For the pressure-velocity coupling, a modified Pressure Implicit with Splitting of Operators (PISO) algorithm was selected. Although more iterations might be required, the PISO algorithm usually shows better performance than other methods for transient simulation. The standard k-ε model (RANS turbulence model) was selected for describing the developed turbulence zone. The model only solves the turbulence scale up to the integral length scale. However, the model was favored due to its simplicity and lower calculation time requirements compared to the Reynolds Stress Model (RSM) or Large Eddy Simulation (LES) models.

The influence of turbulence on the combustion is accounted for through the enhanced mixing process. A RANS turbulence model enhances mixing by introducing a turbulent viscosity. The addition of a turbulent viscosity also eliminates smaller scales within the CFD simulation. Although the turbulent viscosity eliminates smaller scales, it is common for RANS engine combustion simulations to be under-resolved. The lack of sufficient mesh resolution to resolve the remaining scales in a RANS combustion simulation may result in a significant sub-grid term that needs to be modeled. In the context of combustion simulation, it is shown that frequently this sub-grid term is significantly more important than Turbulent Chemistry Interaction terms (TCI). In this simulation, the TCI is not included.

The flow close to the wall is dominated by viscous effects (low Reynolds number) and thus the mean flow velocity depends on the distance from the wall, and gas properties. It may not be possible to resolve this viscous sublayer zone because it requires a very small mesh. To remedy the under-resolved flow, a law of the wall boundary condition was applied. The law bridges the viscous sublayer between the wall and the fully turbulent region. To calculate the spray in a simulation, drop parcels were introduced into the domain at the injector location at a given rate. Parcels represent a group of identical drops (i. e., same radius, velocity, temperaature, etc.) and are used to statistically represent the entire spray field. By using the concept of drop parcels, the computational time of a simulation involving sprays is reduced significantly.

A two-steps reaction was used to model the coal combustion. To account for the radiation, the discrete ordinates (DO) model was selected. The DO model spans the entire range of optical thicknesses, and allows solving problems ranging from surface-to-surface radiation to participating radiation in combustion problems.

The solution strategy is developed to reduce instability of the simulation process. Coal combustion modeling includes several physical processes that could result in numerical stability issue when all processes are solved at once. To guarantee a stable numerical solution, a step-by-step solution process was applied. Initially the combustion and radiation models were turned off and a cold flow simulation was conducted. The convergent result was obtained after running the model for tens of iterations. Then the combustion model was turned on and the model was further run for several iterations to get a convergent result. To maintain stable result, the under-relaxation factor for energy was reduced initially and then increased gradually with the flow time. After the convergent solution was reached, the combustion result was obtained along with a convergent flow field result. Finally, the radiation was turned on and a complete coal combustion result was obtained after running the model for several iterations.

Based on CFD results, Fig. 7 and 8 show CO_2 and CO mass fraction in the near boiler outlet. From this result, the combustion process produces CO and CO_2 gas with increasing CO_2 will be accompanied by decreasing CO. It can be shown that the CO burnout into CO_2 is not complete. This phenomenon can be used as a predictor of effectivity combustion efficiency. The amount of CO produced from each model tends to increase, respectively from model 1 to model 4 is 2.314E-07, 5.878E-07, 5.678E-07 and 7.904E-07. It indicates that combustion process higher on the large oh LHV and smaller coal particle size. These data are connected with the plot of temperature distribution on each model. In the different HHV conditions, the coal particle size has a more significant effect on CO_2 and CO mass fraction. It can be connected that more rapid combustion of the finer particles produces the higher heat reaction plot (Fig. 6, *a*). For further study, the influence of excess air (primary air and secondary air ratio) on the characteristics of combustion processes in the boiler can be developed. NOx distribution report can be explored to ensure emission affected by coal particle size.

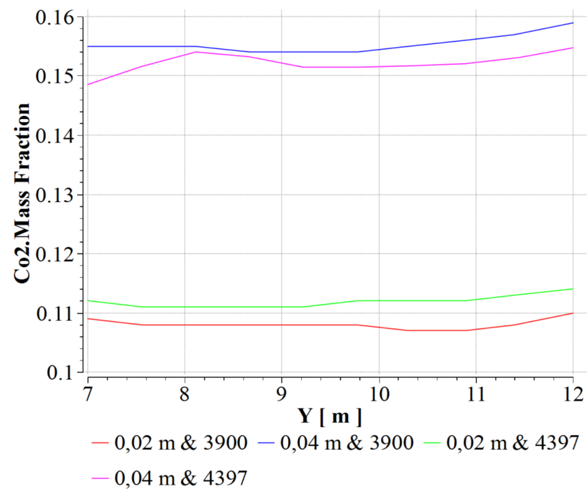

Fig. 7. CO_2 mass fraction for variation of coal particle size and HHV value in the near outlet

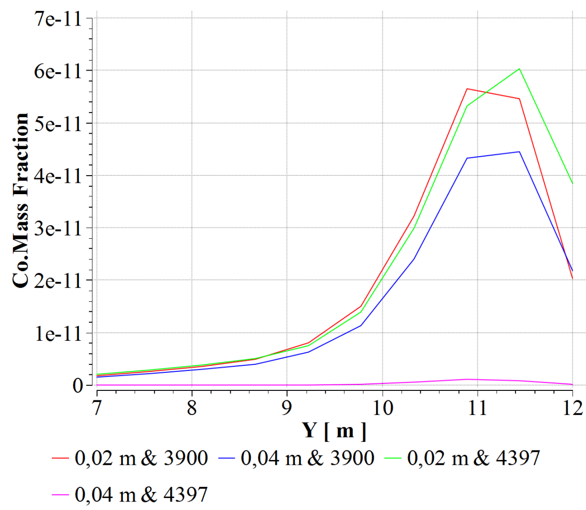

Fig. 8. CO mass fraction for variations of coal particle size and HHV value in the near outlet

7. Conclusions

1. CFD simulation to model the coal properties on combustion characterization in the stoker boiler is developed. Discrete particle Model (DPM) and coal calculator are used. The three stages were used to run the solution of the model.

2. The maximum temperature in the 1st to 4th model is 1440.95, 1473.85, 1347.72 and 1617.17 [K]. The amount of CO produced from each model tends to increase; respectively from 1st to 4th model is 2.314E-07, 5.878E-07, 5.678E-07 and 7.904E-07.

3. Coal particle size has a more significant effect on the temperature distribution and heat of reaction characteristics compared with HHV values.

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