Transient Thermal Response in a Fluidized Bed Reactor

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Abstract

The objectives of this investigation are to determine the heating time required for a ceramic-lined fluidized bed reactor to reach a steady state temperature when starting at room temperature and to study the unsteady thermal reaction of injecting water into the reactor after reaching initial steady state conditions. Numerical methods for this investigation are verified through experimental methods performed at The University of Texas at San Antonio (UTSA) in the Power Dynamics Systems Laboratory (PDL) using the fluidized bed portion of the Biomass Pyrolysis System. The fluidized bed reactor was modeled using MATLAB software and its Partial Differential Equation (PDE) tool box. Various heater settings were used in each test ranging from a nominal 500 watts to near 900 watts. The diameter of the fluid bed is 9 cm with a height of 20 cm containing sand with a nominal particle diameter of 400 μm.

This investigation provides insight into the heating time of the reactor. Also, modeling the reactor and comparing the calculated results to the experimental results aids in the design of fluidized beds for various processes, which may use different types of insulations, sand sizes, or fluidizing gases. Comparable results were obtained between the numerical model and experimental studies.

Introduction

Background

This study experimentally and computationally investigates the transient heating characteristics of the fluidized bed located in the Power Dynamics System Laboratory (PDL) at The University of Texas at San Antonio (UTSA). This study was undertaken to gain more insight into this type of fluidized bed and to understand the transient response of the fluidized bed while heating and injecting water. Water was selected as the fluid to simulate the injection of biomass particles during actual pyrolysis tests.

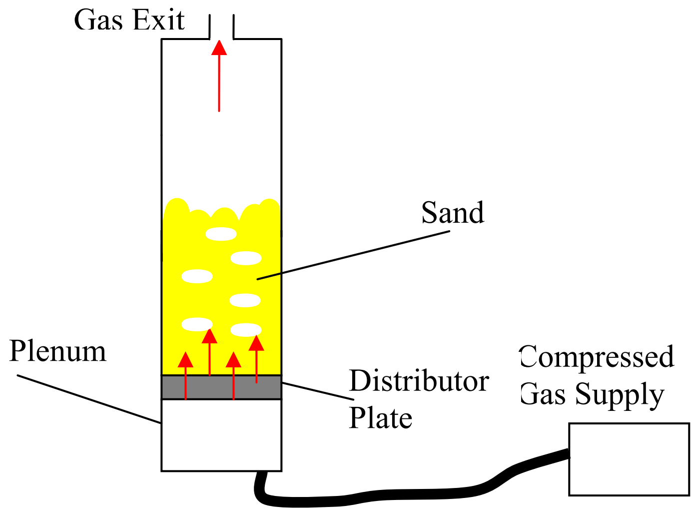


Figure 1: Main fluidized bed components

Fluidized bed reactors are usually vertical cylindrical shells that can be insulated and are often used for chemical transformation of substances. Fluidized beds can be used to enhance thermo-chemical changes of solid biomass particles into a mixture of products[1]. In fast pyrolysis, the reactions produce char, liquid and non-condensable gases that can be separated by cyclones and condensers[2]. In Figure 1, the critical components of a fluidized bed reactor are detailed. Pressurized gas passes through a round sintered plate into the fluid bed from a plenum connected to a gas supply. An inert carrier gas is often used for the application of biomass conversion via pyrolysis into bio-oil. The purpose of having a sintered plate is to supply gas uniformly across the bed cross-section at low gas velocities into the sand bed. Note, fluidization is defined as a process in which fine solid particles interact with flowing gas resulting in the solid particles behaving as a fluid. In fact, movements of the solid particles in a fluid bed act very similarly to a boiling liquid[3].

The importance of this study

There is still a need for understanding the heating characteristics of the fluid bed in order to design commercial size fluid beds to perform these conversions. Historically, scaling problems result with fluid bed design[4] because of a lack of understanding of the heating characteristics. This investigation clarifies the heating characteristic of a fluid bed through the use of numerical simulations and experiments. Also, the numerical simulation can be modified to scale up a fluid bed to predict the heating characteristics of the commercial size fluid beds.

The University of Texas at San Antonio's (UTSA) bench type fluidized bed reactor is primarily utilized in the experimental work of this study. This fluidized bed reactor has a total of sixteen thermocouple and pressure ports for system monitoring. This reactor is heated by eight Watlow electrical cartridge heaters. Each heater rod has a length of eight inches and a maximum power capacity of 1000 Watts at 240 Volts AC. The heaters are configured vertically around the sand bed in 45˚ increments.

Methods

Energy flow in the fluidized bed

The energy equation[5] for the system described by Figure 2 is shown by Equation (1), which is applied to the fluidized bed. The left side of the equation represents the rate of energy storage terms for the sand bed and surrounding ceramic namely $\frac{dE_{sand}}{dt}$ and $\frac{dE_{ceramic}}{dt}$.

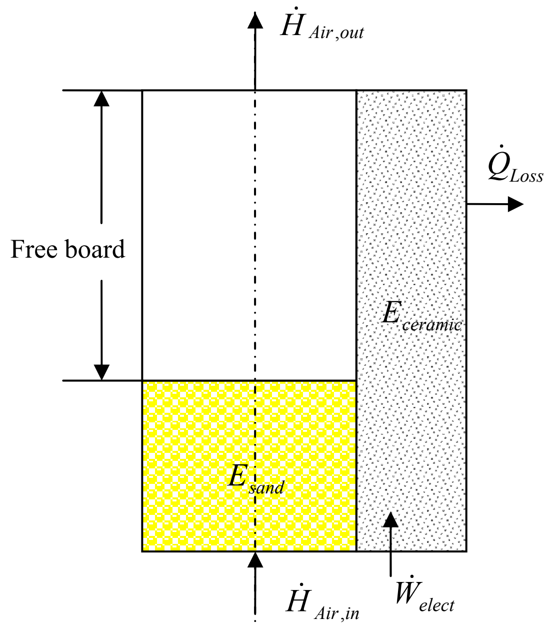


Figure 2: Energy flow in the fluidized bed

The purpose of having the ceramic material at the outer surface of the bed is to keep energy stored in the sand bed region of the fluidized bed reactor. Note, heat is stored in the ceramic region from electrical heaters and provides transient heat addition at the surface of the sand bed.

$$\frac{dE_{sand}}{dt} + \frac{dE_{ceramic}}{dt} = +\dot{W}_{elect} - \dot{Q}_{Loss} + \dot{H}_{Air,in} - \dot{H}_{Air,out} \quad \textbf{(1)}$$

The right side of the equation is represented by $\dot{W}_{elect}$, the electrical power input to the heaters; $\dot{Q}_{Loss}$, the heat loss due to free convection heat transfer on the outer surface of the fluidized bed reactor; $\dot{H}_{Air,in}$, the enthalpy rate of the air, at room temperature entering the sand bed and $\dot{H}_{Air,out}$, the enthalpy rate of air exiting the fluid bed reactor. Typically inert gases are used in fluid beds as a carrier gas. However, in this investigation, oxygenated air was used because of accessibility to compressed air and little possibility of significant reactions such as combustion.

Fluidized bed model development

In order to develop a finite element model for the fluidized bed, there are multiple steps that must be taken into account. These steps include selecting a coordinate system for the model, selecting the geometry of the model, deciding on governing equations for the main calculations, selecting proper boundary conditions, discretization of the main equations and the boundary conditions, determining the property constants, and then developing a computer program that will calculate the desired variable. The temperature profile is the primary variable sought in this fluidized bed model.

Fluid beds usually have a cylindrical shape; thus, the heat diffusion equation in cylindrical coordinate system is utilized. The heat equation, illustrated as Equation (2), suggests the temperature (T) is a function of radial (r), circumferential (θ), and axial (z) directions and time (t).

$$\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(k\cdot r\cdot\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(k\cdot\frac{\partial T}{\partial\theta}\right)+\frac{\partial}{\partial z}\left(k\cdot\frac{\partial T}{\partial z}\right)+\dot{q}=\rho\cdot C_p\left(\frac{\partial T}{\partial t}\right) \quad \textbf{(2)}$$

with $T=T(r,\theta,z,t)$

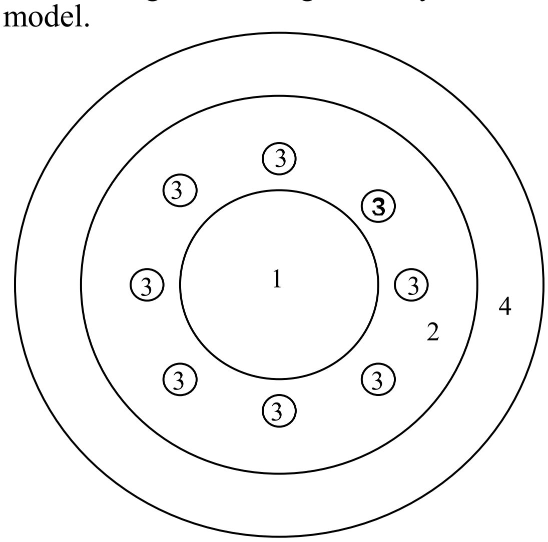
Four different variables, three of which are spatial (r, θ, and z) and the fourth temporal (t), make the computation time of the CPU potentially large[5]. The temperature in this model is considered constant in the axial direction. As a result, the *z* direction in Equation (2) can be eliminated making the temperature profile a function of the radial (r), circumferential (θ) and time (t) as shown in the Equation (3).

$$\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(k\cdot r\cdot\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(k\cdot\frac{\partial T}{\partial\theta}\right)+\dot{q}=\rho\cdot C_p\left(\frac{\partial T}{\partial t}\right) \quad \textbf{(3)}$$

$T=T(r,\theta,t)$

Geometry of the fluidized bed model

Figure 3 shows the two dimensional top view of the modeled fluidized bed consisting of eight electrical heater rods located in a circular ring spaced 45˚ apart. The inner ceramic (2) and outer ceramic (4) regions are shown in the Figure 4 noting that they have different material properties, which are considered in the model.



1. Sand bed, r = 4.5 cm
2. Inner ceramic region, r = 8.4 cm
3. Heater, r = 0.79cm
4. Outer ceramic region, r = 12.5cm

Figure 3: Top view of fluidized bed model

Background of the Partial Differential Equation (PDE) Toolbox

The Partial Differential Equation (PDE) Toolbox is a software that works in conjunction with MATLAB. This program provides a preprocessor and defines a partial differential equation problem. It also creates the two dimensional regions, defines boundary conditions and defines partial differential equation coefficients[6]. In addition, it generates free meshes, discretizes the partial differential equations, solves the discretized equations numerically and also visualizes the results in graphs or by animating the results.

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = \dot{Q} + h(T_{ext} - T) \quad \textbf{(4)}$$

The PDE Tool Box can handle parabolic and hyperbolic partial differential equations as well as eigenvalue problems. However, in this investigation the heat equation correlates with parabolic differential equation type as shown in Equation (4).

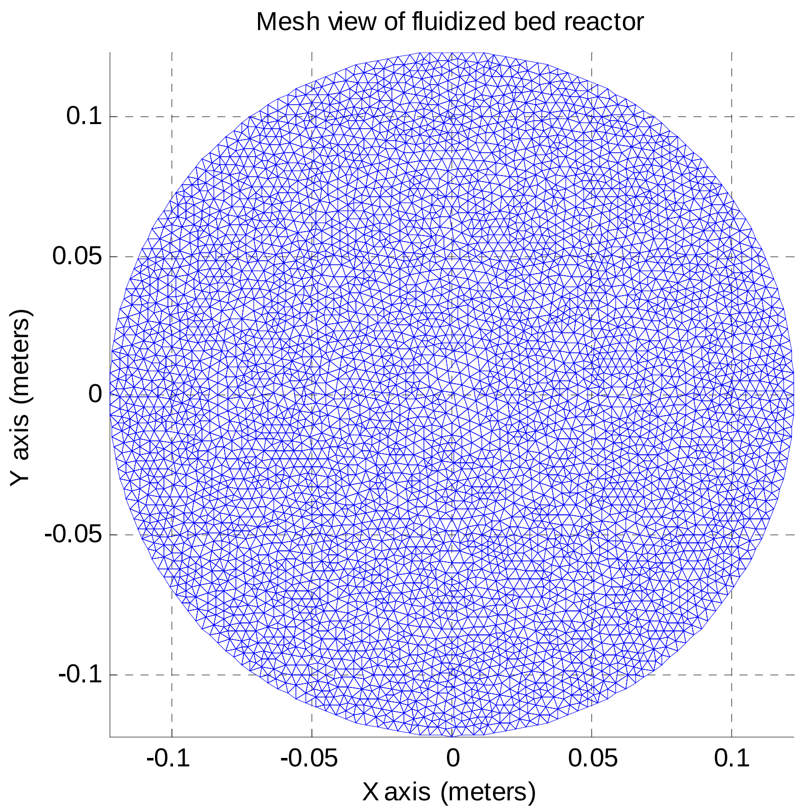


Figure 4: Mesh view of fluidized bed reactor

Figure 4 is the mesh of the fluidized bed reactor obtained with MATHLAB PDE Tool Box. In this mesh triangular type of mesh is used with a characteristic dimension of 2 mm.

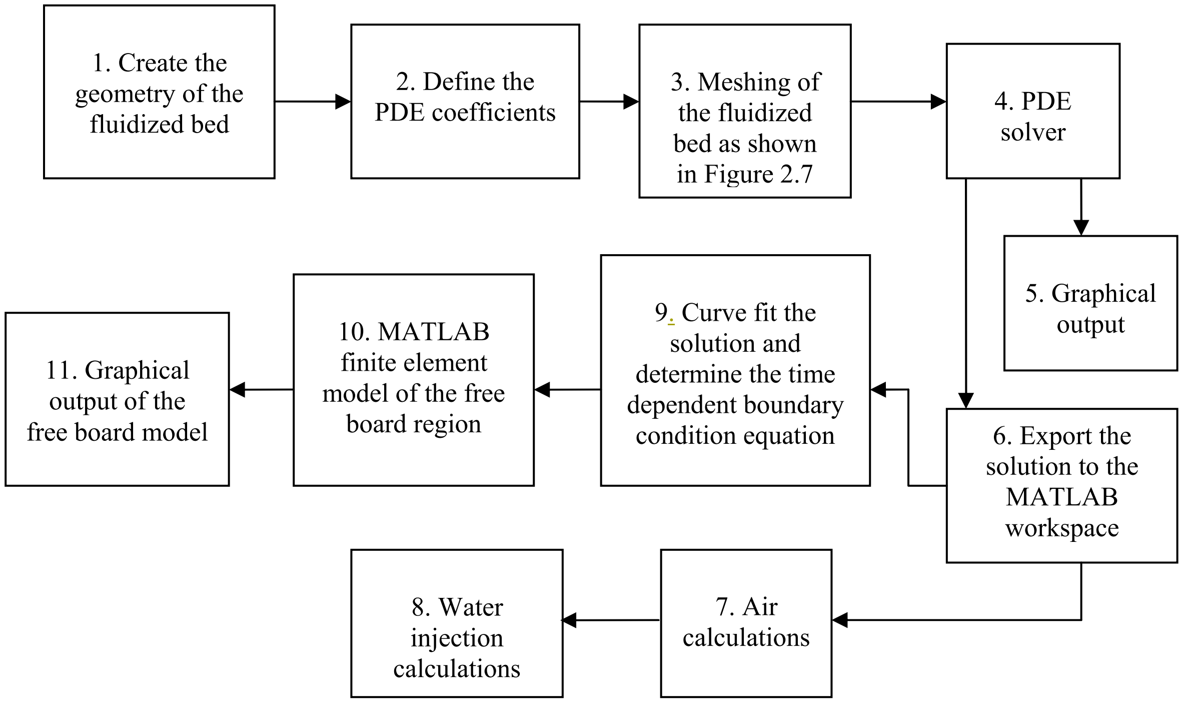


Figure 5: Finite element model development with PDE Tool Box and MATHLAB

The flowchart shown in Figure 5 illustrates the steps that were taken in the numerical analysis.

Experimental

Five thermocouples are located at the bottom, top and at the exit of the bed, as well as at a point at the inner and outer ceramic insulation of the fluidized bed. Eight Watlow Firerod cartridge heaters having a length of 20 cm, a diameter of 1.59 cm and (240 Volt, 1000 Watts) were used as a heat source in the fluidized bed reactor. The voltage was controlled by a power controller unit made by Payne Engineering (model of 18-D-2 30i)[7].

The water flow rate was calibrated before and measured during each experiment. The procedure to determine the water flow rate is to measure the initial mass of water at time zero and then measuring the water remaining after the elapsed time. The mass flow rate of water was assumed steady and uniform as it was injected into the fluid bed.

Test procedure:

The inlet airflow was set at 3.87 kg/hr into the fluidized bed in each experiment. The voltage and the current of each heater was measured by a voltmeter and ammeter to determine the heat addition to the unit at predetermined setting. The fluidized bed reactor was heated until the bed temperature reached steady state. Water was then injected representing the endothermic nature of biomass pyrolysis. Also, water properties can be obtained easily in most thermal science books[1]. The water flow rate of 0.59 kg/hr was calculated as the thermal load equivalent to the selected biomass flow rate of 2.0 kg/hr. The experiment continued until the bed reached a secondary steady state temperature, and it is defined as $\Delta T / \Delta t$ which is 0.2 ˚C per minute.

Results and Discussion

3.1 Experimental Results

A total of six experimental runs were completed to determine the steady state heating time and the length of the unsteady time while injecting water into the fluidized bed reactor. Three of the runs were successful out of the six attempted. The successful runs were numbered 2, 5, and 6, however for brevity only Run 6 will be discussed in detail. Note that Runs 2 and 5 yielded similar results.

In Run 6 (Fig. 6), the fluidized bed reached the steady state temperature 493˚C in about 6.81 hours and the fluidized bed temperature reached the secondary steady state in an additional 1.98 hours and temperature decreased to 343˚C.

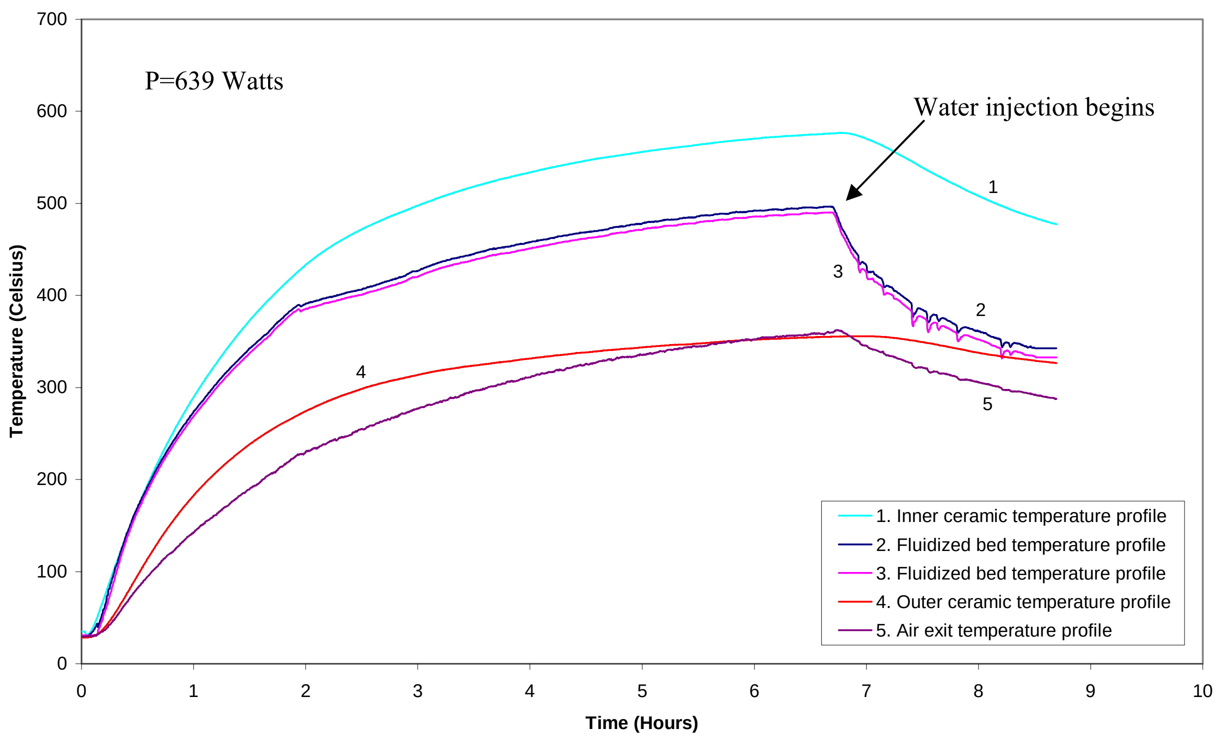


Figure 6: Temperature profile of the fluidized bed during Run # 6

Numerical Results

All input data utilized represents Run 6 including the heater power, which was 79.9 watts per heater. The surface boundary condition was set as a convective boundary condition with a convection coefficient of 15 W/(m^2-K). Figure 7 shows the simulation result of Run 6.

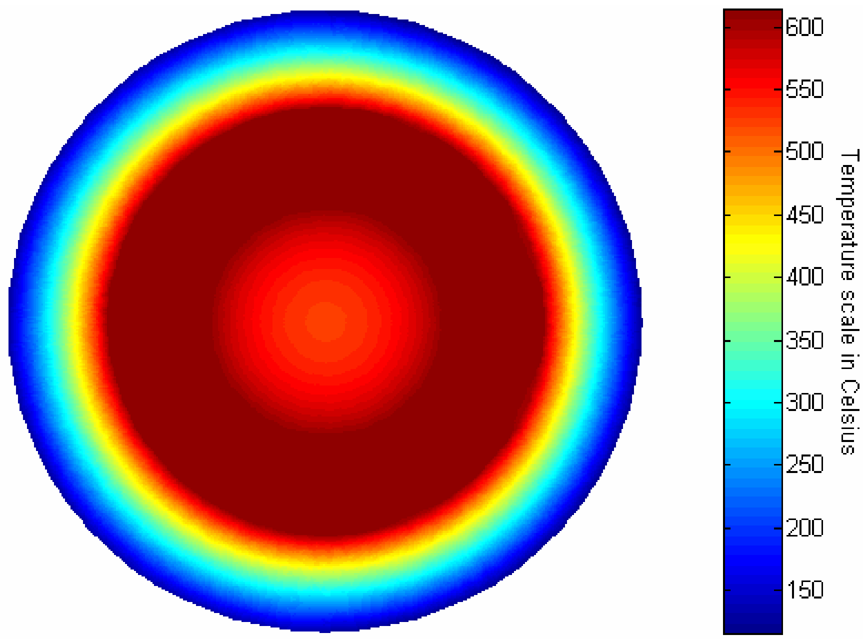


Figure 2: Finite element model (PDE) results for Run # 6

Comparison of Experimental and Numerical Methods

The comparisons of heating characteristics of the fluidized bed are shown in Table 1. The numerical results have a faster heating response compared to the actual experimental runs. One possible reason for this response is heat loss in the axial direction.

Table 1: Numerical and experimental results when heating the fluidized bed

	Numerical results		**Experiment results**	
	Temperature ˚C	**Time in hours**	**Temperature ˚C**	**Time in hours**
Run 5	483	5.90	451	5.84
Run 6	527	6.74	492	6.74

The numerical and experimental results of water injection into the fluidized bed are shown in Table 2. The finite element model reached the secondary steady state at a higher temperature compared to actual experimental runs.

Table 2: Numerical and experimental results of water injection into the fluidize bed

	Numerical results of water injection		**Experimental results of water injection**	
	Temperature ˚C	**Time in hours**	**Temperature ˚C**	**Time in hours**
Run 5	340	2.01	334	1.99
Run 6	359	1.94	333	1.98

The finite element model solution was improved as shown in Figure 8. In order to improve the solution, one of the parameters of the model was adjusted. The parameter representing the conductivity of sand was selected as 1.9 W/m-K, which corresponds to the particle conductivity and it was utilized in all previous results. The volume average bulk sand conductivity 1.1 W/m-K was used instead of the sand particle conductivity. Also, the heat transfer coefficient of the fluidized sand was adjusted to 350 W/m^2-K.

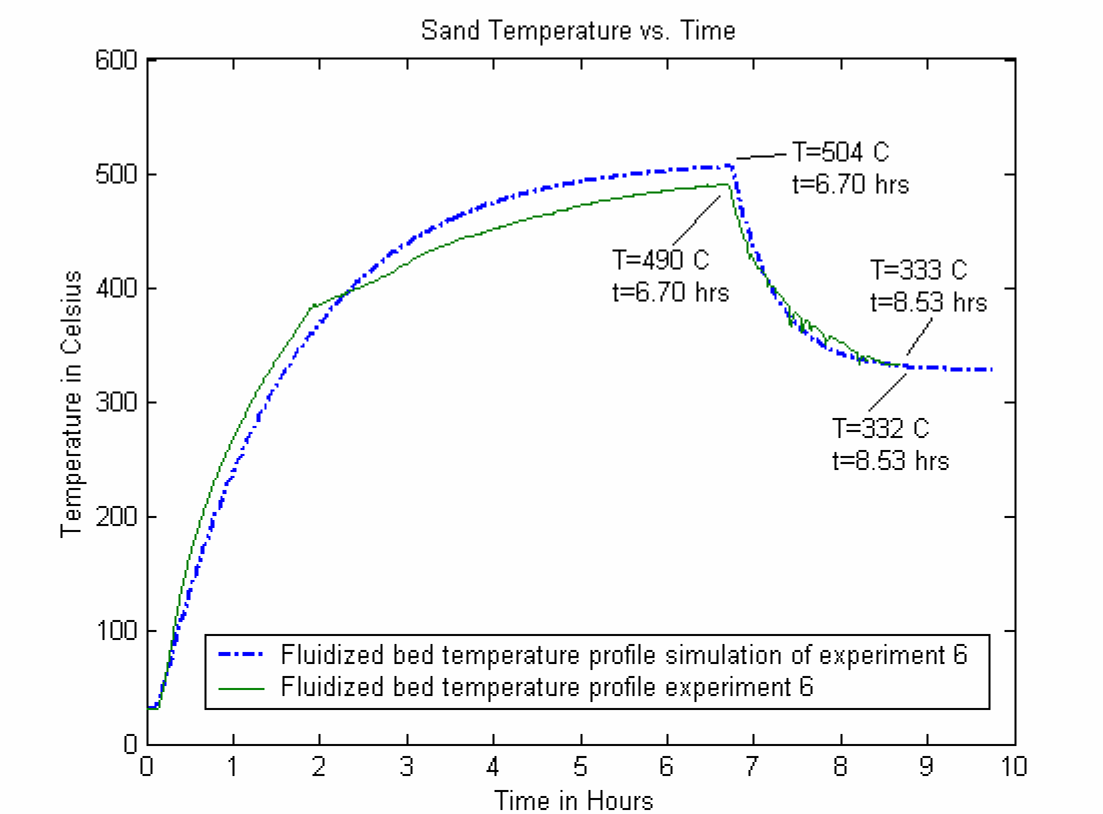


Figure 8: Comparison plot's of numerical results versus Run 6 results with k correction

The temperature of the fluidized bed model reached the steady state of 504˚C in 6.70 hours, and in Run 6 the temperature reached the steady state 490˚C in 6.70 hours. The fluidized bed temperature reached the secondary steady state temperature of 332˚C in 1.83 hours after injecting water. The result was verified with experimental data which was obtained in Experiment 6, and this was the temperature of 333˚C in 1.83 hours.

Summary and Conclusions

This investigation studies the heating time required reach a steady state bed temperature in a fluidized bed reactor. Also investigated is the secondary steady state resulting from injecting water into the fluidized bed. The numerical model of the fluidized bed was successfully completed. In order to determine the transient temperature profile of the fluidized bed reactor, the heat equation in cylindrical coordinates was solved.

The investigation of water injection into the fluidized bed also showed that the biomass pyrolysis system at The University of Texas at San Antonio (UTSA) should operate at the mass flow rate of 0.2 to 0.3 kg/hr of water to avoid the large temperature declines. These water flow rates are equivalent to mass flow rates of 0.68 to 1.02 kg/hr of biomass. Heater power settings of 80.2 to 89.3 watts should be utilized to prevent damage of heaters, which can occur at heater temperatures of 1020˚C.

The heating time of the fluidized bed reactor was determined by using numerical simulations and these results were verified with experimental data. The numerical simulations were improved by using the bulk conductivity of sand instead particle conductivity.

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