International Journal of Innovation and Scientific Research
ISSN 2351-8014 Vol. 14 No. 2 Apr. 2015, pp. 178-187
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http://www.ijisr.issr-journals.org/

Devolatilization of Wood in Fluidized Beds-A Review of Research on Experiments and Modelling

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ABSTRACT: This paper presents a detailed review of experimental and modeling work carried out on devolatilization of different kinds of wood under fluidized bed combustion/pyrolysis conditions. Laboratory scale experimental studies as well as analytical, phenomenological and numerical modeling works have been reviewed and presented. It has been found that attempts to determine the kinetics in actual fluidized bed conditions have been carried out. There is no single devolatilization model that incorporates all the physical and chemical phenomena occurring during devolatilization. Moreover, the physical phenomenon of primary fragmentation has not been adequately incorporated in the models. Also, non-intrusive temperature measurement techniques need to be developed and demonstrated.

KEYWORDS: Wood, Devolatilization, Experiments, Modelling, Review.

1 INTRODUCTION

Devolatilization of wood, which usually occurs in the range of 600-900 K, is the initial stage in the overall combustion process of wood during which the constituent volatiles are released and burned leaving char as the residual product. Also, devolatilization happens in a much shorter time than char combustion. Due to the high volatile content of wood (>70%), a major portion of the heat content is released during devolatilization. A devolatilizing solid wood particle undergoes mostly three physical changes: volumetric shrinkage, mass reduction and primary fragmentation (breakage of the fuel into smaller sizes of char during devolatilization), which control the subsequent char yield, its size and mass distribution. This in turn influences the char combustion process and the char combustion time itself, which could be several times longer than the devolatilization time. Hence a study of devolatilization is essential to obtain qualitative and quantitative information on devolatilization time, char yield and char size distribution to facilitate proper combustor design and operation.

2 PHYSICAL MODEL

A pictorial description of the environment and the processes a wood particle wood undergo in a fluidized bed is given by Sudhakar and Kolar [1]. A wood particle in a fluidized bed mostly behaves as if it exists alone. This is because in a fluidized bed, the fuel consists of only 2-5% of the total bed mass. The wood particle undergoes heat and mass interactions which dictate the 'Thermal Behaviour'. It also undergoes physical changes like shrinkage and fragmentation which dictate the 'Physical Behaviour' of the wood particle. Also, the released volatiles burn under oxidation conditions and the char too may partly undergo combustion before devolatilization process is completed. During its residence period in the bed, the wood particle moves turbulently within and also on top of the bed.

This paper deals with the Thermal Behaviour. The 'Thermal' aspects are described by the spatial and temporal variation of temperature inside the wood particle along with heat generation and shrinkage. The temperature distribution depends on the initial size of the wood particle, its shape, the amount of shrinkage it undergoes and the kinetics governing the devolatilization process. The thermal aspects can be determined experimentally and can also be predicted by a thermal model which considers important parameters and gives as output the spatial and temporal temperature distribution. The obtained temperature distribution can be used to determine the devolatilization time and char yield. Also, the gas composition and yield can be measured and determined analytically using detailed models.

3 LITERATURE DEALING WITH EXPERIMENTS ONLY

In one of the earlier works reported by Kita et. al. [2], cylindrical wood particles of size 20 mm have been used to determine the devolatilization temperature in a fluidized bed at 923 K. Leckner et. al. [3] have used cylindrical wooden pellets of size 4-29 mm in a bed fluidized with oxygen at a temperature of 873-1173 K. They have determined the process kinetics using analytical models of devolatilization and combustion.

de Diego et al [4] have conducted experiments in a a 50 mm ID and 0.5 m tall lab scale fluidized bed reactor with Air/Nitrogen as the medium. They used debarked wet pine wood of irregular shape to determine the devolatilization time (τ_d) and gas composition. The time was determined by two methods-visual and gas analysis of O_2 and CO_2 and were found to be almost same. They also found that the devolatilization time was not influenced by the medium, O_2 or N_2 and char combustion did not commence during devolatilization. They have also proposed a correlation to determine the devolatilization time using the initial wood size, equivalent diameter and a shape factor.

de Diego et. al. [5] have experimentally investigated the influence wood moisture on the devolatilization time. Pinus Sylvestris wood cuboids were used at sizes 15×15×15 mm, 20×9×20 mm, 10×16×15 mm, 10×10×10 mm and 20×4×20 mm. They have deliberately introduced moisture into the wood particles and left them for a week to have a stabilized moisture content. They found that the τ_d increased linearly with increase in moisture content and the slope of this rise increased when bed temperature was lowered. The devolatilization time was correlated using a power law relation (τ_d=ad^n) in which the value of the power 'n' varied between 1.5 and 1.7 and was unaffected by bed temperature and moisture content.

Di Blasi and Branca [6] have measured the transient centre temperatures in long cylindrical wood particles (*l*=20 mm, d=2 to 10 mm) devolatilizing in a bed of sand fluidized with nitrogen and maintained at a bed temperature of 800-1100 K. They have determined the devolatilization time from the measured temperature and proposed a correlation for devolatilization time as a function of cylinder diameter and bed temperature. This is one of the few temperature measurements in a fluidized bed combustor reported in literature. Their measurements revealed that the heating rate at the particle center is a strong function of the conversion level; that is, pyrolysis of wood for the conditions typically established in fluidized-bed reactors is controlled by the rate of internal heat transfer in wood.

Kumar et al. [7] have conducted experiments in a lab scale fluidized bed (130 mm dia and 600 mm tall) to determine the devolatilization time of Casuarina Equisetifolia wood in a lab scale facility fluidized by air. They have considered cylindrical wood with different aspect ratio resulting in disks, cylinders and rods. The influence of initial wood size and bed temperature has been studied and correlation for devolatilization time has been proposed. The size of the cylindrical wood particles is represented by the size of a sphere having the same volume to surface area ratio. The structure of the equation is similar to that given by de Diego et al. [5].

Wang et al. [8] have pyrolysed various types of wood (pine, beech, demolition wood) in a batch wise operated fluidized bed facility. Conversion times, product yields, and product compositions were measured as a function of the particle size (0.7-17 mm), the vapor's residence time (0.25-6 s), the position of the biomass particles in the bed (dense bed or splash zone), and the fluid bed temperature (523-1073 K). It was observed that for pyrolysis temperatures between 723 and 823 K, the bio-oil yield appeared to be maximal (about 65 wt %), while the water content of the bio-oil is minimal. The position of the biomass particles in the fluid bed, either in the dense bed or in the splash zone, does not affect the conversion time and product yields to a large extent during pyrolysis at 773 K.

Rapagna and Ceslo [9] have conducted experiments on spherical wood (Ostrya Carpinifolia) particles of 5-25 mm size in a fluidized bed having olivine as inert material. The operating temperature was 700-900 ^{0}C and the fluidizing velocity was kept equal to u_{mf}. They have investigated the influence of the fluidizing medium (nitrogen or steam-nitrogen) and found that the medium does not influences the devolatilization time. They have also found out that the location of particle feeding (on the bed or inside the bed) effects the gas yield and maximizes it when the wood is fed deep inside in nitrogen-steam fluidized bed. Maximum char yield, minimum tar and char production were observed at high bed temperatures and low wood sizes.

Sreekanth et al [10], [11] have conducted experiments in a 130 mm diameter 600 mm tall lab scale fluidized bed reactor using air as the medium and sand as the inert material. They have used Casuarina wood of different sizes (10-30 mm) and shapes (cuboid, sphere, cylinder). They have measured the devolatilization time, wood char size as the devolatilization progresses and the mass during devolatilization. They have used the basket technique to retrieve the wood particle from the bed to measure the size and mass. The size was found to decrease due to shrinkage in radial and longitudinal directions and also due to primary fragmentation. This data was used to develop a simple model to determine the end char size which becomes an important input to subsequent char combustion model. Also, the mass of the particle during devolatilization was used to determine the apparent kinetics which can be used in modeling the devolatilization process.

Sudhakar and Kolar [12] have carried out a systematic study of the influence of initial shape and size of wood and bed temperature on the devolatilization time and char yield. It was observed that the initial wood particle size has the strongest influence followed by shape and bed temperature. They have derived a correlation to determine the devolatilization time of wood and could predict their results within 20% accuracy while other's results with 30% accuracy. Char yield was found to vary between 9% and 14% and showed no definite influence of any of the operating parameters. They have also presented a brief literature study to show the status in this field.

Miccio and Russo [13] and Miccio et al. [14] have conducted experiments on birch and spruce wood particled to determine the devolatilization time and also to find the influence of pelletizing when compared to non-pelletizing. Their experimental facility and technique was similar to that of Sreekanth et al. [10]. They have used 10-30 mm pellet size. They found that spruce pellets take longer than birch wood, consistent with their respective volatile matter content. Interestingly, they found that primary fragmentation did not take place. Also, pelletized wood had a longer devolatilization time that non-pelletized wood.

Sreekanth [15] has also reported the results related to measurement of transient shrinkage as a cylindrical wood particle devolatilizes in a fluidized bed at three bed temperatures. It was noticed that longitudinal shrinkage begins after 50% conversion while radial shrinkage begins at the start of devolatilization. In all present models, if shrinkage is incorporated, it is done linearly. Hence the results of Sreekanth [12] are found to be useful in incorporating the actual shrinkage rate in devolatilization models. He also proposed correlations for the shrinkage in radial and longitudinal directions.

Reschmeier et al [16] have developed a technique to determine kinetics data for wood pellets in a fluidized bed. They have used a combination of gravimetric and optical techniques to determine the kinetics of mass reduction and tar production. The fluidized bed is 228 mm in diameter and 350 mm tall and has quartz sand as inert material. It is fluidized by nitrogen gas. They have developed and used analytical method which uses the measured data to predict the kinetics. Such data is useful since present day models use kinetics data obtained in purely gravimetric study facilities using fuel powders. However, the kinetics determined by Reschmeier et al [16] are apparent kinetics as there is limitation of the pyrolysis heat transfer and diffusion.

Ceslo et al. [17] have conducted experiments in a 110 mm diameter stainless steel fluidized bed containing olivine particles of dia 0.48 mm and density 2500 kg/m^3(almost same as that of silica sand). Olivine was chosen for its catalytic activity which favours the conversion of tar. Spherical Ostrya carpinifolia wood was used as fuel and nitrogen gas was used to fluidize the bed. The kinetics were determined from the measured evolution data of hydrogen, carbon monoxide, carbon dioxide and methane.

4 LITERATURE DEALING WITH MODELLING ONLY

Semino and Tognotti [18] have developed a general one dimensional model and applied it to cylindrical wood particles after incorporating internal convection and heat generation while neglecting moisture content and shrinkage. They have also performed a sensitivity analysis to study the influence of various parameters on the model outcome. They have found out that heat transfer coefficient is influential only till a value of 150 W/m^2.K. The char yield was found to increase with wood size. Wood composition influences the yield as hemicellulose and cellulose are more reactive than lignin. Model results have been compared with experimental results (reported elsewhere) carried on poplar wood.

Di Blasi [19] has modeled the fast pyrolysis of cellulosic particles in fluidized beds in order to predict the liquid product yield. A one dimensional cylindrical coordinates model was developed by incorporating internal convection and heat generation while neglecting moisture and shrinkage. The fuel particle size and bed temperature greatly influence the heating rate while the window of conversion was narrow between 600-725 K. Hence the conversion time depends on size and temperature while the product yield is more or less constant.

Grammelis and Kakaras [20] have developed a model for combustion of wood in a fluidized bed. They have integrated devolatilization as well as combustion with combustion of volatiles occurring and radiating the heat back to the wood particle. They have assumed spherical and isothermal (lumped capacity) wood particles thus simplifying by a great deal. They have investigated the effect of uncertain parameters on model predictions and found that wood particle diameter, moisture content, oxygen concentration and the bed temperature have considerable influence. They found that the time necessary for conversion is less for woods than for coal. Particle diameter, moisture content, oxygen concentration and gas temperature have significant influence on the model results.

Saastamoinen [21] has proposed a new model for pyrolysis which can be implemented as a sub-model in a CFD code and is suitable for different fuels including biomass with varying size, reactivity, moisture and shape. It is a 1-D model including heat and mass diffusion and heat of reaction but neglecting shrinkage. The model is yet to be validated with experimental data. Devolatilization was approximated to be taking place a particular temperature called pyrolysis temperature. The model could simulate the effects of particle shape (cuboid, cylinder, sphere), size, moisture, density and reactivity. Shrinkage has been neglected.

Sreekanth et al [22] and Sreekanth and Kolar [23] have developed a two dimensional transient thermal model in cylindrical coordinates to predict the devolatilization of cylindrical wooden particles. They have incorporated the effect of moisture, shrinkage, heat generation but neglected internal convection. Experimentally determined shrinkage values have been linearly fit to the progress of conversion. The conversion has been determined by a typical temperature attained by a location. When that temperature is attained by the centre, the conversion is said to be complete. The model could successfully predict the experimentally measured centre temperatures of Di Blasi and Branca [6]. Also, the contours of isotherms, wood density, moisture content in the wood particle have been predicted. It was noticed that the conversion progresses faster across the grains than along them. Incorporation of shrinkage was found to be useful in predicting better results. Also, thermal wave propagation was faster in 2D model than in a 1D model.

5 LITERATURE DEALING WITH BOTH EXPERIMENTS AND MODELLING

Di Felice et al. [24] have conducted experiments on wood devolatilization in a fluidized bed and adopted a novel technique to monitor the gas production. They have continuously monitored the bed pressure which showed peaks corresponding to maximum gas production. They have also developed a model for devolatilization in 1-D spherical coordinates which was compared with published data and also with the experiments. Good comparison was found between the computed peak in the gas production and the pressure measured. Experiments were conducted in a 62 mm diameter fluidized bed reactor which is small enough to justify the pressure measurement technique used to correlate devolatilization. Accurate pressure measurements will be needed and extension of the technique to larger facilities is not yet verified.

de Diego et al. [25] they have conducted experiments on cuboidal pine wood particles under inert and oxidation conditions. They have also studied the influence of initial wood size, bed temperature and moisture on the devolatilization time of wood under fluidized bed combustor conditions. They have also developed a devolatilization model in spherical coordinates and incorporated shrinkage and drying while the kinetics have been modeled based on the Distributed Activation Energy Model. This model has been first used by Chirone et al. [26] to predict the devolatilization in a spherical coal particle. de Diego et al [25] have found that moisture has a telling influence on the devolatilization time and they have also proposed a correlation for devolatilization time which considers the size of the cuboids as that of a sphere having the same volume to surface area ratio. During the experiments they have visually noticed that the volatiles evolution is more during the initial few seconds and decreased towards the end.

Jand and Foscolo [27] have studied the devolatilization of wood particles and the combustion/gasification of the remaining char in a bubbling bed of sand fluidized by nitrogen, steam and air. They have also proposed a model in 1-D spherical coordinates that considers heat transfer to and within the wood particle and a single reaction accounting for the devolatilization process. Within the range of study (wood size 5-20 mm and bed temperature 833-1013 K), the model is found to agree well with the measurements. They found that the fluidization velocity and presence of steam in the fluidizing medium had little influence on the devolatilization time, volatile evolution rate and their composition.

Kersten et al. [28] have reviewed the literature on biomass pyrolysis and have also proposed a detailed model under fluidized bed conditions. From the literature review, they conclude that the available knowledge of kinetics and transport phenomena is not integrated into the reactor design properly and complex 2-D models do not provide any better results than the 1-D models for engineering calculations. They have proposed an expression to evaluate the effective pyrolysis temperature which is essentially the average particle temperature at which the conversion is taking place. They have also noticed that the kinetic constants can be used only to obtain the general trends and are not able to predict the product yields accurately except for the conditions under which they have been derived. This emphasizes the importance of determining the kinetics in actual fluidized bed conditions to be applied to fluidized bed models.

Luo et al. [29] have developed a model for flash pyrolysis of wood in a fluidized bed in order to predict the production of pyrolysis oil. They opine that fluidized bed technology is a suitable method to produce high quality bio-oil. They have conducted experiments in an atmosphere of nitrogen at 500-700 ^{0}C. The effect of main operation parameters on wood pyrolysis product distribution was well simulated. The model shows that reaction temperature plays an important role in wood pyrolysis. A good agreement between experimental and theoretical results was obtained. It was shown that particles less than 500 μm could achieve a high heating-up rate to meet the demands of flash pyrolysis.

Kumar et al. [30] have conducted extensive experiments in a lab scale fluidized bed using cylindrical wood particles (*Casuarina Equisetifolia*) with shape varying from disks to long rods. They have measured shrinkage in the longitudinal as well as tangential directions and proposed correlations for the same as a function of size and bed temperature. Experiments were conducted at a bed temperature ranging from 650-850 ^{0}C. They found that longitudinal shrinkage is lower than radial (transverse) shrinkage and the average volumetric shrinkage is 47%. This data is a useful input to devolatilization models. However, they have measured the terminal shrinkage and not the progressive shrinkage during devolatilization. Hence the shrinkage data can only be incorporated only in a linear fashion along the progress conversion.

Sreekanth et al. [31] have conducted experiments on cuboidal and cylindrical wood particles at a bed temperature of 850 ^{0}C. The bed was fluidized by air preheated to 400 ^{0}C. They have incorporated the shrinkage determined by Kumar et al. [30] in the model used to predict the devolatilization time and char yield. The model has been extended to predict the behaviour of cuboidal shape wood by transforming a cuboid to a cylinder having same height and same surface area. The experimental results have been predicted to an accuracy of 20%. The model too could predict the results of Di Blasi and Branca [6]. The study also showed that the external heat transfer coefficient has no significant influence on the devolatilization time beyond a value of 300 W/m^2.K. Also, particle shrinkage did not influence the devolatilization time but has influenced the char yield.

Sudhakar et al. [32] have conducted experiments and modeled the devolatilization of Casuarina wood in a bubbling fluidized bed. This is the only three dimensional model till date in this field. The model included the phenomena of shrinkage, heat generation, moisture and anisotropy apart from variable properties. They have conducted a sensitivity study of various model input parameters on the devolatilization time and char yield. They found that initial density, thermal conductivity and specific heat have most significant influence while the external heat transfer coefficient has little influence beyond 500 W/m^2.K. They also found that the model results are sensitive to kinetic parameters and hence the appropriate values must be used. This finding again emphasizes the need to determine the kinetics in actual fluidized bed conditions.

Ceslo et al. [17] have developed a simple model in one dimensional spherical coordinates. They have mostly relied on analytical solutions of the transient heat conduction equation and the reaction rate equations. They have not incorporated any of the shrinkage, heat generation, internal convection and drying phenomenon. They have used a pyrolysis kinetics model and a statistical model to predict their experimental measurements of gas evolution rate and times. They found that the statistical model could predict the influence of temperature on gas yield while the pyrolysis kinetics model failed to. They conclude that increasing the bed temperature increases the gas yield while the pyrolysis time is decreased by reducing the particle size.

Bu et al. [33], [34] have conducted detailed experiments in a two dimensional fluidized bed combustor having a provision to view the proceedings in the bed through a quartz wall. Studies were conducted in oxygen rich atmosphere at a temperature of 1088 K (= 815 ^{0}C). They have also measured the particle centre temperature by a thermocouple. However, this could have restricted the randomness of fluidization in the bed. They found that the devolatilization times are longer in O_2/CO_2 atmosphere than in O_2/N_2 atmosphere. Also, the influence of the flame attached to the wood particle has no influence on devolatilization time. They have also developed a one dimensional spherical coordinate model to simulate the process. The model predicts the particle and flame temperature with good accuracy. The model also predicts that only a small amount of the flame obtained by burning volatiles in transferred to the wood particle.

The consolidated literature analysis is presented in the tables below:

Table 1: Literature Review of Experimental and Modelling Work on Devolatilization of wood in Fluidized Beds

S. No	Author	Fuel	Fuel Shape (Expt)	Fuel Size (mm)	Bed Temp. (K)	Fluidizing Medium	Model Details					
							Dimensions	Shape	Moisture	Internal Convection	Shrinkage	Heat Generation
1.	Kita et. a. [2]	Wood	Cylinder	20	923	Air	No modelling reported					
2.	Leckner et al. [3]	Swedish Wood pellets	Cylinder	d=6-10 l=4-29	873 - 1173	Oxygen	No modelling reported					
3.	de Diego et. al. [4]	Pine wood	Irregular Cuboid	7-37 4-40	923, 1023, 1123, 1223	Air Nitrogen	No modelling reported					
4.	de Diego et al. [5]	Pine wood	Cuboid	10×10×10 10×16×15 15×15×15 20×4×20 20×9×20	923, 1023, 1123, 1223	Air Nitrogen	No modelling reported					
5.	Di Blasi & Branca [6]	Beech wood	Cylinder	l=20 d=2-10	712-1107	Nitrogen	No modelling reported					
6.	Kumar et al. [7]	Casuarina wood	Cylinder, Cube	5-30	923, 1023, 1123	Air	No modelling reported					
7.	Wang et. al. [8]	Pine wood	Cylinder	l=42 d=0.7-17	523-1073	Nitrogen	No modelling reported					
8.	Rapagna & Celso [9]	Ostrya Wood	Sphere	5-25	973-1173	Nitrogen/ Steam	No modelling reported					
9.	Sreekanth et. al. [10]	Casuarina Wood	Cuboid, Cylinder, Sphere	10-30	1173	Air	No thermal modelling reported					
10.	Sreekanth et al. [11]	Casuarina Wood	Cylinder	d = 10 to 30	1023,1123,1223	Air	No modelling reported					
11.	Sudhakar & Kolar [12]	Casuarina Wood	Cube/Cylinder/ Sphere	10,15, 20,25	1023, 1123, 1223	Air	No modelling reported					
12.	Miccio & Russo [13]	Beech and Spruce Wood & Coal	Cylindrical	6	1023	Air	No modelling reported					
13.	Miccio et al. [14]	Beech and Spruce Wood/ Coal	Pellets	6	963	Air	No modeling reported					
14.	Sreekanth [15]	Casuarina Wood	Cylinder	d = 10 to 30	1023,1123,1223	Air	No modelling reported					
15.	Reschmeier et. al. [16]	Wood Pellets	Cylindrical	6	1123	Nitrogen	No modelling reported					
16.	Ceslo et al. [17]	Ostrya Wood	Sphere	d=5, 10, 15	973, 1073, 1173	Nitrogen	Kinetics based modeling described later					
17.	Semino & Tognotti [18]	No experiments conducted					1D	Cylinder	No	Yes	No	Yes
18.	Di Blasi [19]	No experiments conducted					1D	Cylindrical	No	Yes	No	Yes
19.	Grammelis & Kakaras [20]	No experiments conducted					1D	Sphere	Yes	Yes	No	Not mentioned
20.	Saastamoinen [21]	No experiments conducted					1D	Cuboid, Cylinder Sphere	Yes	Yes	No	Yes
21.	Sreekanth et al. [22]	No experiments conducted					2D	Cylinder	Yes	No	Yes	Yes
22.	Sreekanth & Kolar [23]	No experiments conducted					2D	Cylinder	Yes	No	Yes	Yes
23.	Di Felice et al. [24]	Almond	Irregular	0.53-45	773 973 1073	Nitrogen	1D	Sphere	No	Yes	No	Yes
24.	de Diego et. al. [25]	Pine wood	Irregular	7-37	923-1223	Air Nitrogen	1D	Sphere	Yes	No	Yes	No

25.	Jand & Foscolo [27]	Beech wood	Sphere	5-20	833 943 1013	Air Nitrogen	1D	Sphere	No	No	Yes	No
26.	Kersten et al. [28]	Pine Peech Bamboo	Cylinder	0.4-30	523-1073	Nitrogen	1D 2D	Cylinder	Yes	Yes	No	No
27.	Luo et al. [29]	Wood	Sphere	<0.5 mm	773, 873, 973	Nitrogen	1D	Sphere	No	Yes	Yes	Yes
28.	Kumar et. al. [30]	Casuarina Wood	Disc, Cylinder, Rod	5 to 100	1123	Air	2D	Disc, Cylinder, Rod	No	No	Yes	No
29.	Sreekanth et al. [31]	Casuarina Wood	Cylinder	d=4, l=20 & d =10, l = 50	1123	Nitrogen	2D	Cylinder	Yes	No	Yes	Yes
30.	Sudhakar and Kolar [32]	Casuarina Wood	Cube	10,15,20,25	1023, 1123, 1223	Nitrogen	3D	Cube	Yes	No	Yes	Yes
31.	Ceslo et al. [17]	Ostrya Wood	Sphere	0.005, .01,.015	973,1073,1173	Nitrogen	1D	Sphere	No	No	No	No
32.	Bu et al. [33], [34]	Schima Wood	Sphere	d=6 mm	1088	O_2/N_2, O_2/CO_2	1D	Sphere	No	No	No	No

Table 2: Details of Experimental Facility

S. No	Author	Shape of the Reactor	Dimensions of the Reactor (mm)	Inert Bed Material, size	Fluidizing Velocity (m/s)
1	de Diego et. al. [4, 25]	Cylinder	ID=50 H=50	Silica Sand, 550 µm	0.4
2	Di Blasi & Branca [6]	Cylinder	ID=63 H=450	Calcined sand, 180-250 µm	0.036
3	Kumar et. al. [7, 30]	Cylinder	ID=130 H=600	Silica Sand, 500 µm	NM
4	Wang et. al. [8]	Cylinder	ID=26 H=45	Silica Sand, 258 µm	0.032
5	Rapagna & Celso [9]	Cylinder	ID=110 H=NM	Olivine, 480 µm	NM
6	Sreekanth et. al. [10, 11,15, 22, 23, 31]	Cylinder	ID=130 H=600	Silica Sand, 550 µm	0.5
7	Sudhakar & Kolar [12, 32]	Cylinder	ID=130 H=600	Silica Sand, 375 µ	u/u_{mf}=5
8	Miccio & Russo [13,14]	Cylinder	ID=120 H=500	Silica Sand, 325, 600 µm	0.11, 0.21
9	Reschmeier et. al. [16]	Cylinder	ID=228 H=350	Quartz sand, 60-200 µm	NM
10	Ceslo et al. [17]	Cylinder	ID=110 H=NM	Olivine, 480 µm	NM
11	Di Felice et al. [24]	Cylinder	ID=62 H=NM	Alumina (103 µm), Silica Sand (500 µm)	NM
12	Jand & Foscolo [27]	Cylinder	ID=110 H=NM	Sand, 380 µm	u/u_{mf}=2-4.8
13	Kersten et al. [28]	Cylinder	ID=26 H=45	Silica Sand, 258 µm	0.032
14	Luo et al. [29]	Cylinder	ID=80 H=1200	NM	NM
15	Bu et al. [33, 34]	Rectangle	200 × 20 × 400	Silica Sand, 250-350 µm	0.28

NM: Not mentioned

OBSERVATIONS ON THE EXPERIMENTAL FACILITIES USED

i. Most fluidized bed reactors are cylindrical in shape while only Bu et. al.[33,34] have used rectangular one. They have used one of the faces transparent to be able to view the proceedings inside the reactor.

ii. The inner diameters ranged from 26 mm to 228 mm while most of the reactors have around 100 mm dia. The variation in heights is quite large.

iii. Sand has been used as the bed material commonly although alumina and olivine have been used too. However, the densities of alumina, olivine and sand are in the same ball park. The inert bed particle size ranged from 60 µm to 550 µm.

iv. Some works have not reported the fluidizing velocities. However, from the above data, it is noted that the ratio u/u_{mf} ranged between 1 and 5.

6 Conclusions

6.1 Experimental

i. Very few wood species have been studied in fluidized beds. Most species are from the European region while very few are from Asia.

ii. Devolatilization time has been mostly measured by two techniques: Visual and Gas composition. A third method of bed pressure change has been proposed by De Felice et. al. [24].

iii. Temperature measurement of wood particle is carried out by very few researchers by using invasive technique like a thermocouple. This could influence the fluidization behaviour. The error introduced by such a method needs to be addressed. Also, non-intrusive techniques need to be developed.

iv. Determination of devolatilization kinetics in an actual fluidized bed combustor is still in a nascent stage. The main problem in measuring the kinetics is the accurate mass measurement of the wood particle.

v. All the experiments have been carried out in small reactors. The effects of scaling up the results must be investigated.

vi. No study has been conducted to understand the influence of Primary Fragmentation on volatiles release rate.

vii. Apart from the temperature measurement inside the particle, the pressure measurement too needs to be carried out to determine the influence of the out flowing volatiles and their influence on the external heat transfer coefficient.

6.2 Modelling

i. Most of the models are either one dimensional or two dimensional. Only one model of Sudhakar and Kolar [32] has modeled in three dimensions for a cuboidal wood particle. Three dimensional models in cylindrical coordinates is needed badly as cylinder is the natural shape of wood.

ii. There is not a single model which incorporates the influence of shrinkage, internal convection, moisture content and heat generation together.

iii. The kinetics used in the models have been determined in standard TGA experimental facilities which use powdered fuel and the heating rates are low. The need of the hour is to design a method to accurately determine the kinetics in an actual fluidized bed reactor.

iv. It has been concluded that the external heat transfer coefficient has no influence on the thermal behaviour beyond a certain value. Hence extremely accurate heat transfer coefficient models are not needed as long as a simple model predicts a reasonably accurate value.

v. Presence of Oxygen in the fluidizing medium has no influence on the devolatilization time and the heat transferred back to the wood particle from the volatiles flame, Bu et al. [34].

vi. No model has considered the influence of Primary Fragmentation on the devolatilization rate even though it is obvious that the former could accelerate the latter. Hence size reduction due to fragmentation needs to be incorporated in models which deal with wood that fragments within the early stages of devolatilization.

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