TABLE OF CONTENTS

Abstract	
Acknowledgments	
List of tables, figures, abbreviations, symbols	
1. Introduction	1-8
	2
1.1. Biomass Scenario in India	2
1.2. Objective of the present work	7
2. Literature review	9-44
2.1 Biomass.	9
2.2. Physical and Chemical Properties of Crop Residues	10
2.2.1 Physical Properties	10
Moisture Content	10
Bulk Density	11
2.2.2. Chemical Properties	12
Ultimate Analysis	12
Proximate Analysis	12
Heating Value	13
Ash Composition	14
2.4.5. Table of Proximate and Ultimate analysis	
2.3. Utilization of Crop residues	15
2.4. Thermo chemical conversion of biomass to Energy	16
2.4.1. Pyrolysis	17
2.4.2. Combustion	17
2.4.3. Gasification	18
2.5. Gasification reaction network and gasification products	19
2.5.1 Pyrolysis	20
2.5.2 Gasification reactions	21

,

.

Gasification with air	22
Gasification with steam	24
Gasification with carbon-dioxide	24
Additional reactions occurring during gasification	25
Tar	25
Ash	27
2.6. Gasification Facilities for Biomass Gasification	28
2.6.1 Fixed bed gasifiers	28
2.6.2 Fluidized bed gasifiers	30
2.6.3. Entrained bed gasifier	32
2.7. Gasifier Applications	32
2.7.1. Direct Heating	32
2.7.2. Power Generation	32
2.7.3. Methanol Production	33
2.8 Fluidized Bed Hydrodynamics	33
2.8.1 A general description of Fluidization	34
2.8.2 Regimes of Fluidization	34
2.8.3 Parameters affecting fluidization behavior	. 35
2.8.4 Cold flow BFB model	36
2.8.5 Particle Characteristics	36
2.8.6 Void fraction	37
2.8.7 Minimum fluidization velocity	38
2.8.8 Terminal velocity of particles	38
2.8.9 Bubble behavior:	39
3. Modeling of fluidized bed gasification	45-65
3.1 Modeling of Fluidized Bed Air Gasification	

3.1.1Mass Balance

- 3.1.2 Thermodynamic Equilibrium
 3.1.3 Heat Balance
 3.2 Equilibrium Modeling of Steam Gasification
 3.2.1 Mass Balance
 3.2.2 Thermodynamic equilibrium
 3.2.3 Heat Balance
 4. Basic Design Methodology of a Bubbling Fluidized-Bed Gasifier
 4.1. Reaction Chamber
 4.1.1. Minimum fluidization velocity
 4.1.2. Fluidization velocity during the gasification
 4.1.3. Terminal velocity of the particle
 4.1.4. Reactor diameter
 4.1.5. Bed height
 - 4.2. Distributor design
 - 4.3 Calculation of the Cyclone separator

5. Experimental methodology

Experimental apparatus

- 5.1. Cold Model Study
- 5.2. Hot Model Study
 - 5.2.1. Pellet Maker
 - 5.2.2. Fuel Feeder
 - 5.2.3. Bubbling Fluidized Bed Reactor
 - 5.2.4. Air Supply Unit
 - 5.2.5 . Start-up Burner
 - 5.2.6. Distributor Plate
 - 5.2.7. Cyclone

5.3 Measurement and Data Acquisition Systems

- 5.3.1 Gas Sampling System
- 5.3.2. Data Acquisition System

78-84

66-78

.

6. Results and discussions	86-118
6.1 Effect of Equivalence Ratio on Molar Concentration	
6.1.1 Effect of ER on H ₂ and CO	85
6.1.2 Effect of ER on CO ₂ and CH ₄	88
6.1.3 Effect of Moisture on Molar Concentration	90
6.2. Model Sensitivity Analysis	93
6.2.1 Effect of reactor temperature	93
6.2.2 Effect of Steam Biomass Ratio (S/B)	95
6.3 Model validation	96
6.3.1 Air Gasification	96
6.3.2 Model validation for steam gasification	107
6.4 Experimental Result	110
6.4.1 Effect of the Equivalence Ratio on Gas Composition	110
6.4.2 Bed Temperature	113
7. Conclusions	116-118
REFFERENCES	119-129

 1.1	Experimental graph between pressure drop and Air velocity	4
1.2	Biomass power in India	5
2.1	Moisture Content of Some Crop Residues	11
2.2	Bulk Density of Some Crop Residues (Dry Basis)	11
2.3	Ultimate analysis of some biomass materials (dry Basis)	13
2.4	Proximate analysis of some biomass materials (dry Basis)	13
2.5	Higher Heating Value of Some Biomass Materials	14
2.6	The main chemical reactions in gasification processes	22
2.7	Typical tar loading for biomass gasifiers	26
3.1	Heat capacity constants A, B, C and D	51
3.2	Heat of formation at 298.15 K in kJ/kmol	52
3.3	Gibbs functions of formation at 298.15 K in kJ/kmol	52
3.4	Polynomial coefficients for enthalpies and Gibbs functions Benson et al.	55
4,1	Physical properties of rice husk and sand	68
4.2	Design parameters for the air distribution plate.	73
6.1	Effect of the temperature in the bed during biomass gasification in	94
	fluidised bed with pure steam	
6.2	Effect of the steam/biomass (S/B) ratio in biomass gasification in	97
	fluidised bed with pure steam.	
6.3	Cold model experimental investigation	117

LIST OF TABLES

i

Figure No.	Particulars	Page
		No.
1.1	Primary Energy Sources in India	3
2.1	Competing Uses of Crop Residues	15
2.2	Thermo-chemical conversion of biomass to energy route	16
2.3	Temperature Profile in a particle during heating-up	19
2.4	Pyrolysis of a wet fuel particle containing elements C, H, O, S and N	20
	and products of devolatilization and drying.	
2.5	Updraft Gasifier	29
2.6	Downdraft gasifier	29
2.7	Fluidized bed reactor (Bubbling and circulating respectively)	30
2.8	States of fluidization	31
2.9	General concept of Fluidization	34
2.10	Different Regimes of Fluidization	35
2.11	Parameter affecting Fluidization behavior	35
2.12	Graph between bed voidage and sphericity of particles	37
2.13	Bubble Structure	41
3.1	Flow chart for Equilibrium modeling of Air gasification process using biomass	55
3.2	Flow chart for predicting Reactor temperature in Air gasification process	59
4.1	Zens and Weil correlations to TDH calculation	70
4.2	Sketch of biomass gasifier	72
4.3	Schematic of a Cyclone separator along its relative dimensions	76
4.4	larger of either the inlet or outlet velocity is used	77
5.1	Cold model BFB diagram	79
5.2	Pellet maker for making pellet of Rice husk	81
5.3	Fuel feeding subsystem	82

LIST OF FIGURES

5.4	Bubbling Fluidized bed Gasifier experimental set up	83
5.5	Cyclone used in the gasifier	84
5.6	Gas Chromatograph for product gas sample analysis	85
6.1	Molar fraction of H ₂ with varying ER at varying temp MC=10%	87
6.2	Molar fraction of H_2O with varying ER at varying temp MC=10%	88
6.3	Molar fraction of CO with varying ER at varying temp MC=10%	89
6.4	Molar fraction of CO_2 with varying ER at varying temp MC=10%	90
6.5	Molar fraction of CH ₄ with varying ER at varying temp MC=10%	90
6.6	H_2 Gas Composition with varying MC at Different MC, ER=0.35,	92
	Temp of Bed = 941 OC	
6.7	Molar Fraction of CO at Different MC, ER=0.35, Temp of Bed = 941	92
	0C	
6.8	Molar Fraction of CH_4 at Different MC, ER=0.35, Temp of Bed =	93
	941 0C	
6.9	Gas composition vs. Gasification temperature for Rice Husk at S/B=	96
	0.8	
6.10	Gas composition vs. Steam/Biomass ratio for Rice Husk	97
6.11	Comparison of predicted and Experimental mole fractions of H_2	99
6.12	Comparison of predicted and Experimental mole fractions of CO	99
6.13	Comparison of predicted and Experimental mole fractions of CO_2	100
6.14	Comparison of predicted and Experimental mole fractions of CH ₄	100
6.15	Comparison of Predicted and Experimental HHV	101
6.16	Comparison of Predicted H ₂ composition with experimental result	102
6.17	Comparison of Predicted CO composition with experimental result	102
6.18	Comparison of Predicted CO ₂ composition with experimental result	103
6.19	Comparison of Predicted CH ₄ composition with experimental result	103
6.20	Comparison of Predicted HHV with experimental result	104
6.21	Comparison of Predicted H ₂ composition with experimental result	105
6.22	Comparison of Predicted CO composition with experimental result	105
6.23	Comparison of Predicted CO ₂ composition with experimental result	106

6.24	Comparison of Predicted CH4 composition with experimental result	106
6.25	Comparison of Predicted H ₂ composition with experimental result	107
6.26	Comparison of Predicted CO composition with experimental result	108
6.27	Comparison of Predicted CO ₂ composition with experimental result	108
6.28	Comparison of Predicted CH ₄ composition with experimental result	109
6.29	Gas composition vs. Gasification temperature for Pine Sawdust at	110
	S/B= 0.8	
6.30	Gas composition vs. Gasification temperature for Wheat Straw at	110
	S/B= 0.8	
6.31	Gas composition vs. Gasification temperature for Wheat Straw at	111
	S/B= 0.8	
6.32	Gas composition vs. Steam/Biomass Ratio for Pine wood chips	112
6.33	Equivalent ratio vs H ₂ composition	113
6.34	Equivalent ratio vs CO composition	114
6.35	Equivalent ratio vs CO ₂ composition	114
6.36	Equivalent ratio vs CH ₄ composition	115
6.37	Equivalent ratio vs N ₂ composition	115
6.38	Equivalent ratio vs reactor bed temperature	117
6.39	Experimental graph between pressure drop and Air velocity	118
6.40	Experimental graph between pressure drop and Air velocity	118