

# Design and Experimentation on Two-Stage Biomass Gasification Reactor

R. D. Khonde, [ruta\\_khonde@yahoo.co.in](mailto:ruta_khonde@yahoo.co.in); A. S. Chaurasia<sup>1</sup>, [aschaurasia@che.vnit.ac.in](mailto:aschaurasia@che.vnit.ac.in)

Department of Chemical Engineering, Visvesvaraya National Institute of Technology, Nagpur  
- 440010, India

**Abstract:** Two-stage biomass gasification reactor is a downdraft, fixed-bed reactor having ability to destroy most of the tars produced from pyrolysis of biomass. To study the formation and cracking of tars, a lab-scale two-stage biomass gasification reactor has been constructed. Experiments have been carried out at different operating conditions to study tar formation and its cracking. Experiments has also been carried out for pyrolysis of rice husk at different temperatures for formation of char and the results show that with the increased temperature, char production decreased. For generation of tar from biomass, experiments have been carried out with first stage only and found that all the volatiles by pyrolysis process have been released around 773 K, so the first stage of the reactor is operated at 773 K for all the experiments. To study tar cracking and gasification, both the stages are operated where second stage is empty and operated at different temperatures (873 K, 973 K and 1073 K) so as to crack most of the tar released from the first stage. The results show that the tar content reduced with hot empty second stage or homogeneous vapour phase cracking in second stage.

**Keywords:** Gasification reactor, Down-draft, Fixed-bed, Pyrolysis.

## 1. Introduction

Biomass gasification is not a new technology, but there is a renewed interest in its further development, mainly to produce power and heat. Gasification is the thermal conversion of biomass that takes place at higher temperature and produces the producer gas (CO, H<sub>2</sub>, CH<sub>4</sub> with CO<sub>2</sub>, N<sub>2</sub>) with char, water and condensable vapours as minor products along with the power and heat generation. One very widely used technology for this application is the downdraft fixed bed gasifier. The advantages of this gasifier over other types of gasifier are that the tar and particulates formation occurs at much lower level. Biomass gasification is a developing technology that can be used to achieve an increased use of biomass by generating a product gas rich in H<sub>2</sub> and CO. However, biomass gasification still holds many research and development challenges. In biomass gasification, one of the main operational problems is tar production, which is also an environmental problem. The research and development is being carried out around the world on a wide range of gasification processes in order to minimize tar production and to develop efficient gas cleaning methods.

Tar products formed from biomass gasification in the temperature range of 573-773K [3,11,12,13,10], contains major components of product gas (H<sub>2</sub>, CO, CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>O) in addition to organic (tars) and inorganic (H<sub>2</sub>S, HCl, NH<sub>3</sub>, alkali metals) impurities and particulates. The organic impurities range from low molecular weight hydrocarbons to high molecular weight aromatic hydrocarbons. The low molecular weight hydrocarbons can be used as fuel in gas turbine or engine applications, but are undesirable products in fuel cell

---

<sup>1</sup> Corresponding author.

applications and methanol synthesis. The high molecular weight hydrocarbons are collectively known as tars, and range from single-ring to five-ring aromatic hydrocarbons. The amount of tar and composition varies depending on biomass type, gasifier setup and operating conditions. The tar may exist in the vapour phase in the hot zones of the gasifier, it condense out as liquid droplets in cooling gas. These liquid tars in the product gas are one of the major problems for the application of gasification systems and often cause failure of the gasification projects [1]. The understanding of factors affecting the tar content in the product gas is of major importance in the development of biomass gasification processes. Much work has been done to remove or convert the tar, so far with only moderate success. An overview of this is given by Milne *et.al.*[2].

The two-stage reactor, developed from an earlier single-stage design [3,4], has been modified successfully by Pindoria *et. al.* [5] and used at laboratory scale to produce tars in top section (pyrolysis stage) for subsequent tar cracking in second stage (gasification stage) using catalyst [6,7]. The successive stages in the development of this reactor have been summarized by Kandiyoti *et. al.*[8]. The version of this reactor has been described in several papers [9,10,11,12,13] and modified the equipment so as to add a separate tar destruction unit in series with the existing gasification reactor for maximizing the tar destruction in the reactor. Two-stage fixed-bed downdraft, gasification reactor is also referred as hot-rod reactor or tar cracking gasifier.

In this study, same design of the reactor with certain modifications is fabricated and used for biomass gasification. Some initial experiments of pyrolysis of rice husk at different temperatures are carried out to check the performance of the reactor. Then tar generation using single stage and tar cracking using both the stages have been studied at higher temperatures. Further, heterogeneous tar cracking using different catalysts, residence time study with different reactor lengths, and optimization of conditions in the second stage for minimizing the tar released and maximizing the gas production are planned for future work.

## 2. Methodology

### 2.1 Reactor design

The schematic of newly fabricated two-stage gasifier is shown in figure 1. The reactor body consists of two stages (internal diameter 44 mm and thickness 4 mm) connected together with a throated flange and with a tar trap at the bottom.

*First stage* represents the pyrolysis section of a downdraft gasifier where tar is formed.. The top is fitted with a T-piece, connecting the gas inlet supply and thermocouple measuring the internal reactor temperature. A low, downward flow rate of inert gas (nitrogen) is injected to sweep the products of pyrolysis downwards into the throat section. The bottom of the first stage connects it to the second stage through throat section. *Second Stage* represents the gasification section or tar destruction or high temperature reducing zone, immediately below the inert nozzles of throat section. The second stage may be used empty or packed with a fixed amount of char or catalyst for maximum possible destruction of tar. The bottom of second stage is connected to the tar trap. Another thermocouple is used in this stage for internal temperature measurement for its better control. Both the stages are externally direct resistance heated using PID controllers.

*Throat section* connects both the stages of the reactor. The top flange of throat has been specially designed, having three equally spaced lateral nozzles to enable inert gas to be

injected at the junction of two stages. The throat comprises of a flange with a removable centre-piece having V-shape. The reactor body is insulated to avoid heat radiations in the surrounding. *Tar Trap* is a simple U-tube fitted with a top flange connected to the outlet of second stage via union. It is immersed in cooling agent, like ice and captures/condenses the volatiles released by biomass sample during gasification. For sampling and venting of product gases, a T-piece is fitted at the outlet of the trap.

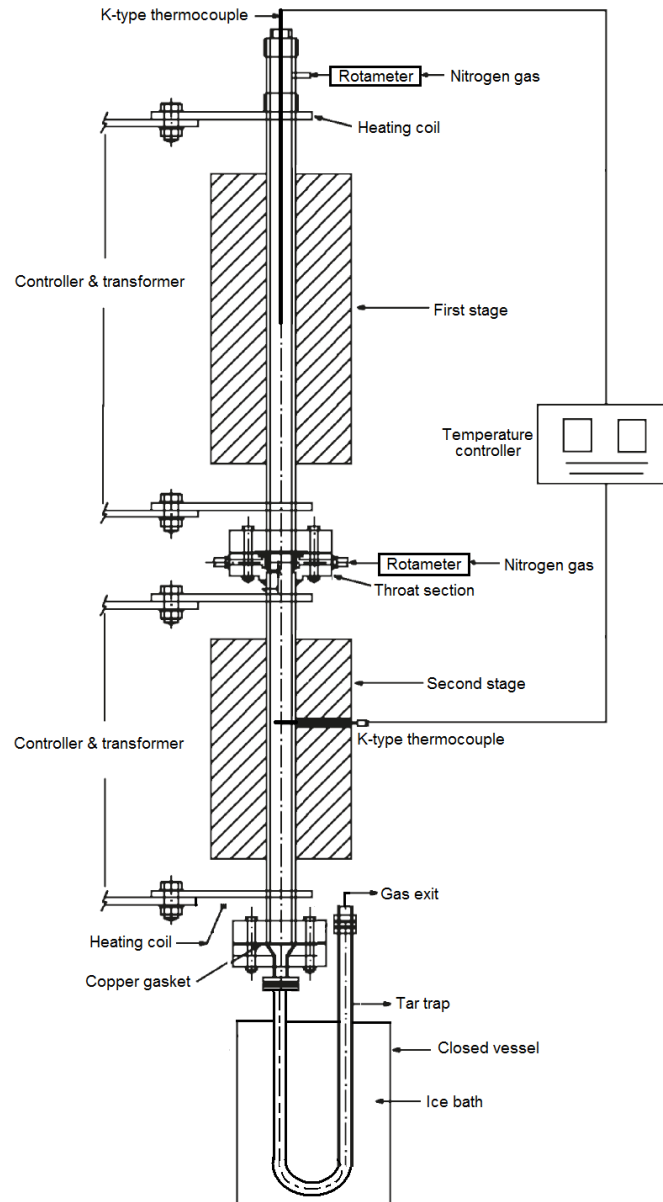


Figure 1: Two-Stage Biomass Gasification Reactor

### 2.2 Reactor operation

The biomass used in this study is rice husk, obtained from a local rice mill. Particle size of less than  $1000\mu\text{m}$  is achieved by grinding and sieving. The biomass is dried in oven at  $105^{\circ}\text{C}$  ( $378\text{K}$ ) for about 6 hours to remove the moisture. The biomass is then stored in air-tight PET containers for further experimentation.

The performance of the reactor has been checked by carrying out some preliminary experiments at different temperature. Here no inert gas is used and hence the gases formed by reaction, escaped from top of the reactor. The experiments has been carried out with 50 g rice husk for each run. The char yield is noted at different temperature, which is repeated atleast twice to verify the obtained values.

For tar formation and cracking, the reactor has been operated in two different modes. In mode-I operation, first stage having length of 257 mm, wis directly connected to the tar trap to determine the tar generated. The operating conditions of this single-stage reactor are: operating temperature 773K, heating rate 25 K/min, sample size of less than 1  $\mu\text{m}$  and sample weight of 50 g. Same criteria has been employed through all the experiments in mode-I and mode-II. As the tar generation takes place mostly in the temperature range of 673-773K [3,12,13], so the operating temperature of 773K is seleted for first stage. During operation, a wire mesh plug is inserted from bottom of first stage to a distance upto 100 mm from the bottom, then the reactor is loaded with biomass sample from the top. One more wire mesh is kept between the joint of reactor and tar trap. The reactor is assembled and heated by externally resistant heating coil to the desired temperature and maintained at that temperature for 15 min using PID controller. One litre per minute (1 LPM) flow of inert (nitrogen) gas through a mass flow controller (rotameter) is also injected from top of reactor to sweep the gaseous volatiles downwards to the tar trap, dipped in ice bath.

In mode-II operation, to study tar cracking and gasification, both the stages having same dimensions are used. Both stages operated and controlled separately; where first stage is always operated at 773K and second stage is empty and operated at different temperatures (873 K, 973 K and 1073 K) so as to crack most of the tar released from the first stage. During this mode of operation, an additional flow of 1 LPM of inert (nitrogen) gas is injected at the throat section. Initially, the second stage is heated and hold to the desired temperature; then the first stage heating is started, so that whatever the volatiles released even at lower temperature of first stage that will be cracked immediately in the second stage which is already maintained at higher temperature.

## **2.3 Products recovery**

### **2.3.1 Char**

When the reaction is over and the reactor is cooled down to room temperature, it is dismantled and the char remained inside the reactor is taken out and weighed. Fine char particles received on the wire mesh and recovered from filtration of tar solution are also weighed and added to total char yield.

### **2.3.2 Tar**

Tar trap is washed several times with a mixture of 4:1 chloroform : methanol untill clear liquid is obtained. The solution is then filtered, first using ordinary filter to reduce the carbon load on the next filtration through Whatman filter paper number 1, and collected in sampling flask of rotary evaporator, which is used to evaporate the solvent leaving tar in the flask. Rotary evaporator is operated at 65°C (as boiling points of chloroforma and methanol are closed to 65°C) and 130 rpm for 15 min. As no extra solvent is used for washing the glasswares, the flask along with the tar is directly weighed when it cooled down to room temperature. The yield of char and tar obtained after each experiment, is reported as a percentage of the initial weight of biomass, on dry basis. Same procedure of recovering the

products from reactor is employed during both modes of operation. In both the modes of operation, every experiment is repeated atleast twice to verify the obtained values.

### 3. Results and discussion

#### 3.1 Char yield

Preliminary experiments on the reactor using rice husk have been performed to obtain char yield at different temperatures, given in table 1. Graphical representation of data, shown by figure 2, indicates that the char production decreases with increase in temperature as at higher temperature most of the char is converted to gas. This indicates proper working of the newly fabricated reactor.

Table 1: Char yield at variable temperature

Temperature (K)	No. of Runs	Weight of char produced (gm)
773	1	19
	2	19.5
873	1	14
	2	13.86
973	1	10.28
	2	10.95
1073	1	7.3
	2	7.2
1173	1	5.85
	2	5.6

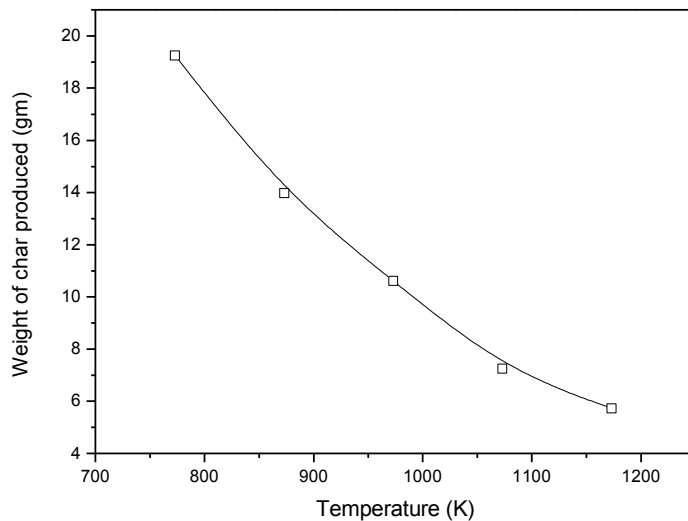


Figure 2: Effect of temperature on char formed

#### 3.2 Tar generation

In mode-I operation of reactor, the biomass is heated from ambient to 773K and decomposed to char by the process of pyrolysis. A series of runs is repeated under the same experimental conditions to determine the amount of tar released by pyrolysis of rice husk.

The data shows good repeatability between the different experimental runs. Char and tar products are recovered by the method already explained and are given in table 2. An average value of 38% of initial biomass is converted to char; whereas 48% is converted to tar. Overall, 60% of the initial biomass weight is converted to gaseous volatile products at 773K. The results are comparable with literature [3,10].

Table 2: Tar, char and gas yields obtained from mode-I operation

No. of runs	Char yield (as % initial weight of biomass on dry basis)	Tar yield (as % initial weight of biomass on dry basis)	Gas evolved*(as % initial weight of biomass on dry basis)
1	38.12	48.62	13.26
2	38.72	49.16	12.12
3	39.38	50.88	9.74
4	37.72	46.66	15.62

\*calculated by difference

### 3.3 Tar cracking

The extent of tar destruction in the mode-II operation of reactor is found by increasing the temperature of reactor. The experiments are performed with an empty heated second stage. The char and tar yields after cracking at higher temperatures are given in table 3. Heated empty second stage at elevated temperatures reduced the amount of tar formed in the second stage of reactor from 48% to 11%. Overall 77% tar cracking is observed in the second stage at 1073K. This gives an effect of time and temperature on secondary reactions that progressively destroys the tar. The data shows good repeatability of runs at different temperatures.

Table 3: Tar yield obtained from mode-II operation

Temperature (K)	No. of runs	Tar yield (as % initial weight of biomass on dry basis)
873	1	35.86
973	1	19.70
	2	20.60
1073	1	11.56
	2	11.68

## 4. Conclusion

The major findings of this work are as follows.

- Char yield decreases with the increasing temperature in newly fabricated two-stage biomass gasification reactor.

- An average of 48% of initial biomass converted to tar in first stage of reactor, which is comparable with literature.
- About 77% tar cracking is observed in the second stage at 1073K.
- Increasing the temperature decreases the tar yield and hence more cracking takes place at higher temperature.

## References

- [1] P. Brandt, E. Larsen, U. Henriksen, “High tar reduction in a two-stage gasifier”, *Energy & Fuels*, vol. 14, pp. 816-819, 2000
- [2] T.A. Milne, R.J. Evans, N. Abatzoglou, “Biomass Gasifier Tars : Their Nature, Formation, and Conversion”, November 1998 \_ NREL/TP-570-25357, National Renewable Energy Laboratory, Golden Colorado, 1998
- [3] M.L. Boroson, J.B. Howard, J.P. Longwell, W.A. Peters, “Product yields and kinetics from the vapor phase cracking of wood pyrolysis tars”, *AIChE*, [Vol. 35, Issue 1](#), pages 120–128, 1989
- [4] R.W. Hiteshue, S. Friedman, R. Madden, “Hydrogasification of High-Volatile A Bituminous Coal”, United States Bureau of Mines Report of Investigation No.6376, 1964
- [5] R.V. Pindoria, J.Y. Lim, J.E. Hawkes, M.J. Lazaro, A.A. Herod, R. Kandiyoti, “Structural characterization of biomass pyrolysis tars/oils from Eucalyptus wood waste: effect of H<sub>2</sub> pressure and sample configuration”, *Fuel*, Vol. 76, No. 11, pp. 1013-1023, 1997
- [6] R.V. Pindoria, A. Megaritis, R.C. Messenbock, R. Dugwell, R. Kandiyoti, “Comparison of the pyrolysis and gasification of biomass: effect of reacting gas atmosphere and pressure on Eucalyptus wood” (Short Communication), *Fuel*, Vol. 77, No. 11, pp. 1247-1251, 1998a
- [7] R.V. Pindoria, A. Megaritis, A.A. Herod, R. Kandiyoti, “A two-stage fixed bed reactor for direct hydrotreatment of volatiles from the hydrolysis of biomass: effect of catalyst temperature, pressure and catalyst ageing time on product characteristics”, *Fuel*, Vol. 77, No. 15, pp. 1715-1726, 1998b
- [8] R. Kandiyoti, A. Herod, K. Bartle, “Solid fuels and heavy hydrocarbon liquids : thermal characterisation and analysis”, Elsevier, Amsterdam, The Netherlands, 2006
- [9] S.M. Nunes, “Investigation of tar destruction reactions in a downdraft gasifier using biomass and waste feedstock”, Ph.D. Thesis, University of London, 2007a
- [10] S.M. Nunes, N. Peterson D.R. Dugwell, R. Kandiyoti, “Tar formation and destruction in a simulated downdraft fixed bed gasifier: reactor design and initial results”, *Energy & Fuels*, vol. 21, pp. 3028-3035, 2007b
- [11] S.M. Nunes, N. Peterson, A.A. Herod, D.R. Dugwell, R. Kandiyoti, “Tar formation and destruction in a fixed bed reactor simulating downdraft gasification: optimization of conditions”, *Energy & Fuels*, Vol. 22, pp. 1955–1964, 2008

- [12] Y. Chen, Y.H. Luo, W.G. Wu, Y. Su, "Experimental investigation on tar formation and destruction in a lab-scale two-stage reactor", *Energy & Fuels*, vol. 23, pp. 4659-4667, 2009
- [13] F. Dabai, N. Paterson, M. Millan, P. Funnell, R. Kandiyoti, "Tar formation and destruction in a fixed-bed reactor simulating downdraft gasification: equipment development and characterization of tar-cracking products", *Energy & Fuels*, vol. 24, pp. 4560-4570, 2010