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# Modeling a stratified downdraft wood gasifier with primary and secondary air entry

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## HIGHLIGHTS

- ▶ A mathematical model of an open-core downdraft gasifier for wood is developed.
- ▶ Dual air entry is simulated: primary air (top) and secondary air (inside the bed).
- ▶ The reaction front structure varies with percentage and position of secondary air.
- ▶ Char and tar conversion is improved by dual air distribution.
- ▶ Good quantitative agreement is obtained between predictions and measurements.

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## ABSTRACT

A detailed mathematical model, comprehensive of the main chemical and physical processes, is proposed for the open-core downdraft gasification of wood pellets, which permits a dual air entry: from the top section (primary air) and at a certain height of the packed bed (secondary air). A transition is simulated from a single, top-stabilized front (zero percentage of secondary air), to a double front stabilization (percentages of secondary air up to 60–70%) and finally to a single, forced center-stabilized front at the position of secondary air injection. For sufficiently high percentages of secondary air, following the complete or partial separation between the zone of primary wood degradation and a high-temperature, oxygen-rich zone and higher temperatures along the char bed, tar and char conversion is highly enhanced. Good agreement is obtained between model predictions and measurements for a pilot-scale plant.



## 1. Introduction

Most of the small-scale biomass gasifiers are of the fixed-bed downdraft type [1]. The open-core design is more flexible than the conventional throated version especially for biomass fuels with troublesome flow characteristics. It consists of a bed supported on a grate, where in most cases [2–6], since the top is open, air is distributed uniformly across the section and the flow is nearly one-dimensional [7,8]. Air and biomass flow concurrently downward. The upper part of the bed consists of biomass particles that may be, in part, pre-heated and dried. Under this region there is the "flaming pyrolysis" layer [7], that is, the decomposition of the solid and the combustion of volatile products in an inadequate supply of air. The third layer consists of a hot char bed where cracking and gasification reactions occurs. Finally, inert char constitutes the fourth layer, where the temperatures are usually too low for the reactions to be active. It serves as a buffer, in the case the flaming pyrolysis zone moves close to the grate, and as a particle filter.

It is desirable to gasify more than 95% of the biomass, leaving only 5% char-ash [7]. However, the amount of unreacted char may reach significant figures, such as 25% of the feed [9]. Moreover, although it is well known that a significant advantage of downdraft gasifiers is that the flow of volatile pyrolysis products across the high-temperature bed causes a relatively low content of tar in the gas, the actual tar conversion depends upon the operating conditions and the design of the gasifier. Typical tar contents of the gas are in the range 10–6000 mg/N $m^3$ versus required values of 50 or 30 mg/N $m^3$ for IC engines and turbines, respectively [10]. Therefore, in order to improve the performances of the open core design, changes have been made in gas re-circulation, insulation of the wall and air distribution into the gasifier. In relation to the latter point, to increase the char burn-out, the so-called double fire design has been proposed [11,12], where some extra air is injected via the grate at the bottom while the producer gas leaves the bed at some distance above. The supply of secondary air, at a certain distance above the grate, was also applied by the Buck-Rogers gasifier [13], as a mean to stabilize the flaming pyrolysis zone and to improve the conversion of tar. A dual air entry (from the top and at a certain bed height) is also foreseen for the open-core gasifiers

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**Nomenclature**

| | |
|---|---|
| $A_i$ | pre-exponential factor |
| $a_1$, $a_2$ | constants in the Clausius–Clayperon relation |
| $A_p$ | particle surface area, $m^2$ |
| $C$ | molar concentration, $kmol/m^3$ |
| $c$ | specific heat, J/kg K |
| $D$ | reactor diameter, m |
| $D_i$ | diffusion coefficient, $m^2/s$ |
| $d_p$ | particle diameter, m |
| $d_e$ | equivalent diameter, m |
| $d_{sph}$ | sphere diameter, m |
| $E_i$ | activation energy, kJ/mol |
| $H_i$ | specific enthalpy, kJ/kg |
| $k_m$ | mass transfer coefficient, m/s |
| $k_m^*$ | maximum value of the mass transfer coefficient, m/s |
| $h$ | heat transfer coefficient, $W/m^2$ K |
| $M$ | molecular weight |
| $m_M$ | moisture evaporation rate, $kg/m^3$ s |
| $p$ | gas pressure, kPa |
| Pr | particle Prandtl number |
| $R$ | air to wood weight ratio, kg/kg |
| $R_g$ | universal gas constant |
| Re | particle Reynolds number |
| $r_j$ | reaction rate, $kmol/m^3$ s |
| Sc | particle Schmidt number |
| $T$ | temperature, K |
| $t$ | time, s |
| $U_g$ | gas velocity, m/s |
| $U_s$ | solid velocity, m/s |
| $V_p$ | particle volume, $m^3$ |
| $X$ | molar fraction, vol% (total basis) |
| $z$ | space, m |
| $W_a$ | air feed rate, kg/h |
| $W_f$ | wood feed rate, kg/h |
| $\gamma$ | stoichiometric coefficient for reaction $c5$ |
| $\nu_p$ | particle density number, 1/m |
| $\nu$ | Stoichiometric coefficient for reactions $p1$, $p2$ |
| $\rho_{W,M}$ | apparent solid density (mass/total volume), $kg/m^3$ |
| $\rho_{C0}$ | constant bed density in the combustion/gasification zone, $kg/m^3$ |
| $\rho_i$ | gas phase mass concentration (mass/gas volume), $kg/m^3$ |
| $\varepsilon$ | porosity |
| $\Delta$ | $\Delta$h reaction enthalpy, kJ/kg |
| $\Lambda$ | moisture (evaporation) enthalpy, kJ/kg |
| $\lambda^*$ | thermal conductivity, W/mK |
| $\mu$ | viscosity, kg/ms |
| $\omega_j$ | combustion or gasification rate, $kg/m^3$ |

*Subscripts*

| | |
|---|---|
| C | CHAR |
| $c1$ | primary tar combustion |
| $c2$ | methane combustion |
| $c3$ | carbon monoxide combustion |
| $c4$ | hydrogen combustion |
| $c5$ | refractory tar combustion |
| $c6$ | char combustion |
| $CH_4$ | methane |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $E$ | equilibrium |
| $g$ | total volatiles (vapor + gas) |
| $gw$ | gas-wall |
| $g1$ | carbon dioxide gasification |
| $g2$ | hydrogen gasification |
| $g3$ | steam gasification |
| $H_2$ | hydrogen |
| $H_2O$ | steam |
| $i$ | chemical species |
| $M$ | moisture |
| max | maximum |
| min | minimum |
| $O_2$ | oxygen |
| $p1$ | primary pyrolysis |
| $p2$ | secondary pyrolysis |
| $s$ | solid (wood + char) |
| $sr$ | steam reforming (1: refractory tar; 2: methane) |
| $sw$ | solid-wall |
| tot | total |
| $T_1$ | primary tar |
| $T_2$ | refractory tar |
| $v$ | vapor |
| $W$ | wood |
| $wg$ | water gas shift |
| $w$ | wall |
| 0 | ambient or initial value |
| $0i$ | secondary air inlet |
| $\alpha$ | H moles in char |
| $\beta$ | O moles in char |
| $\phi$ | sphericity factor |

developed at the Indian Institute of Science, Bangalore (IISc) by Mukunda and coworkers [8,14] and for those developed by SPRERI [15,16]. In general secondary air, injected at about 0.4–0.5 m above the grate [15,16], represents 30–60% of the total inflow, depending on the size of the wood chips and rate of gas flow [8]. A variation in the point of air injection is possible in the pilot-scale gasifier developed by Barrio and coworkers [7–19]. It is shown that a lower air to fuel ratio is required with double air injection (20% from top and 80% inside the char bed) with respect to the traditional open-core design. Multiple secondary air injections are foreseen in a mobile gasifier [20,21]. In this case, the scope is to improve the efficiency of the combustion and tar cracking reactions and to maintain a uniform temperature profile along the char bed, thus also favoring the activity of gasification reactions. Two-air supply stages are also investigated in the experiments carried out by Martinez et al. [22]. It is found that the secondary air stage has a considerable effect on the reduction of the methane concentration of the producer gas, which is taken as an indirect estimate of a similar reduction in the tar content.

Mathematical models, comprehensive of the chief transport phenomena and finite-rate chemical reactions, capable of predicting the performances of downdraft fixed-bed biomass gasifiers have been developed [23–26] aimed at design improvement, search of optimal operating conditions and development of control strategies. However, these only describe the traditional design with air injection from the top, so that the influence of dual air entry on the gasification characteristics has not yet been given consideration and the related action modes have not yet been explained.

In this study a mathematical model is presented for the open-core downdraft gasification of wood pellets which, in addition to the usual air feed at the top of the bed, permits the additional injection of secondary air at a certain height of the bed. A parametric analysis is carried out about the influences of the quantity and position of secondary air on the temperature profile and the conversion of both tar and char for a pilot-scale reactor with the characteristics of that developed by Barrio and coworkers [17–19]. The data reported by these authors are also used to carry out the experimental validation of the model.