LAMPIRAN
**Lampiran 1** Tabel Hasil Percobaan pada kecepatan udara masuk 0,7 m/s

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Lampiran 7 Tabel yield gas, yield arang, yield abu, dan efisiensi pada setiap variasi kecepatan udara masuk reaktor

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<tr>
<th>Kecepatan</th>
<th>Yield Gas (%)</th>
<th>Yield Arang (%)</th>
<th>Yield Abu (%)</th>
<th>Efisiensi (%)</th>
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<tr>
<td>0,7 m/s</td>
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<td>10,29</td>
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<td>23,75</td>
</tr>
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Lampiran 8 Tabel Hasil Percobaan pada variasi campuran 25% arang kayu

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<td>mₜₗ</td>
<td>975</td>
<td>975</td>
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<tr>
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<td>603</td>
</tr>
<tr>
<td>mₗₐₙₚ(sisa)</td>
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<td>68</td>
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<td>mₙₜₖₚ</td>
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<td>T₁</td>
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**Lampiran 10** Tabel Hasil Percobaan pada variasi campuran 75% arang kayu

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### Lampiran 11 Tabel Hasil Percobaan pada variasi campuran 100% arang kayu

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### Lampiran 12 Tabel Distribusi Kenaikan Temperatur Air pada setiap variasi campuran arang kayu

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<td>°C</td>
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Lampiran 13 Tabel Distribusi Penurunan Massa Air pada setiap variasi campuran arang kayu

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**Lampiran 14** Tabel Distribusi kenaikan suhu reaktor pada setiap variasi campuran arang kayu

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<th>50% Arang (°C)</th>
<th>75% Arang (°C)</th>
<th>100% Arang (°C)</th>
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<td>365,1</td>
<td>376,5</td>
<td>391,2</td>
</tr>
<tr>
<td>9</td>
<td>363,9</td>
<td>376,4</td>
<td>384,2</td>
<td>399,3</td>
</tr>
<tr>
<td>10</td>
<td>389,4</td>
<td>412,8</td>
<td>425,3</td>
<td>447,7</td>
</tr>
</tbody>
</table>
Lampiran 15 Tabel yield gas, yield arang, yield abu, dan efisiensi pada setiap variasi campuran arang kayu

<table>
<thead>
<tr>
<th>Variasi</th>
<th>Yield Gas (%)</th>
<th>Yield Arang (%)</th>
<th>Yield Abu (%)</th>
<th>Efisiensi (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% Arang</td>
<td>82,22</td>
<td>16,30</td>
<td>1,48</td>
<td>28,85</td>
</tr>
<tr>
<td>50% Arang</td>
<td>80,07</td>
<td>18,70</td>
<td>1,23</td>
<td>22,17</td>
</tr>
<tr>
<td>75% Arang</td>
<td>78,06</td>
<td>20,86</td>
<td>1,07</td>
<td>18,91</td>
</tr>
<tr>
<td>100% Arang</td>
<td>76,54</td>
<td>22,65</td>
<td>0,81</td>
<td>17,10</td>
</tr>
</tbody>
</table>

Lampiran 16 Perhitungan Menetutkan Kebutuhan Udara

A. *Air Fuel Ratio (AFR)*


\[
AFR = \frac{\text{Massa Udara}}{\text{Massa Bahan Bakar}}
\]

Dari data uji ultimate sekam padi diperoleh kandungan sekam padi adalah \( \text{CH}_{1,65}\text{O}_{0,72} \) dibakar dengan sempurna sehingga menghasilkan gas karbon dioksida (\( \text{CO}_2 \)) dan uap air (\( \text{H}_2\text{O} \)). Reaksi pembakaran sempurna memerlukan udara, dimana kondisi udara stoikiometri adalah \( \text{O}_2 + 3,76 \text{N}_2 \) (Najib, 2012).

\[
\text{CH}_{1,65}\text{O}_{0,72} + 1,05 (\text{O}_2 + 3,76 \text{N}_2) \rightarrow \text{CO}_2 + 0,83\text{H}_2\text{O} + 3,948\text{N}_2
\]

Dari Persamaan diatas dapat kita ketahui massa molekul relatif (MR) dari bahan bakar dan udara dari penjumlahan massa-massa atom relatif (AR) yang terkandung, sehingga kita dapat menentukan nilai AFR.

Analisa ultimate diambil dari *Biomass Gasification and Pyrolysis Practical Design* (Basu, 2010)

\[
\begin{align*}
\text{AR C} & = 47,2 \% \text{ massa} \quad = 3,93 \text{ kmol} \\
\text{AR H} & = 6,5 \% \text{ massa} \quad = 6,5 \text{ kmol} \\
\text{AR O} & = 45,4\% \text{ massa} \quad = 2,84 \text{ kmol}
\end{align*}
\]
MR bahan bakar = (AR C x 1) + (AR H x 1,65) + (AR O x 0,72) 
= (12 x 1) + (1 x 1,65) + (16 x 0,72) 
= 25,22 kg/kmol 

MR udara = 1,05 x (AR O x 2) + 3,76 (AR N x 2) 
= 1,05 x ((16 x 2) + 3,76 ( 14 x 2)) 
= 144,42 kg/kmol 

AFR = \frac{MR udara}{MR bahan bakar} 
= \frac{144,42 \text{ kg/kmol}}{25,22 \text{ kg/kmol}} 
= 5,73 

Dari perhitungan diatas didapatkan AFR untuk bahan bakar adalah 5,76 yang artinya setiap 1 kg bahan bakar udara yang dibutuhkan adalah 5,76 kg. 

B. Laju Aliran Massa Udara 


\[ \dot{m} = \frac{\text{massa udara}}{\text{waktu pembakaran}} \ (\text{kg/detik}) \]

Pada tahap ini penulis melakukan sebuah percobaan pembakaran, yaitu membakar limbah serutan kayu sengon sebanyak 1300 gram dalam kompor gasifikasi. Proses pembakaran dilakukan dari awal hingga hanya tersisa abu pembakaran, dan dari percobaan tersebut didapatkan lamanya waktu pembakaran adalah 35 menit atau 2100 detik. 

Sehingga,

\[ \dot{m} = \frac{5,73 \times 1,3}{2100} \text{ kg/detik} \]
\[ = 0,00355 \text{ kg/detik} \]
C. Kecepatan Udara masuk

Setelah didapatkan laju aliran massa nya, penulis dapat menentukan kecepatan udara masuk yang dibutuhkan untuk terjadi pembakaran sempurna, yaitu menggunakan persamaan berikut : (Najib, 2012).

\[
\dot{m} = \rho \times v \times A \quad (kg/detik)
\]

Keterangan :
\[
\begin{align*}
\dot{m} & : \text{laju aliran massa} \\
\rho & : \text{massa jenis udara} \\
v & : \text{kecepatan udara masuk} \\
A & : \text{luas penampang}
\end{align*}
\]

Untuk mencari kecepatan udara,
\[
v = \frac{\dot{m}}{\rho \times A} \quad (m/detik)
\]

luas penampang yang digunakan yaitu, luas penampang lubang masuk udara yang mana digunakan untuk mengalirkan udara berbentuk lingkaran dan berdiameter lingkaran berlubang D₀ = 11 cm dan diameter rotor Dᵢ = 6 cm, oleh karena untuk mencari luasan menggunakan rumus lingkaran dimana lingkaran berlubang dikurangi lingkaran rotor.

Diketahui:

\[
\begin{align*}
\dot{m} &= 5,73 \times \frac{1,3 \text{ kg}}{2100 \text{ detik}} \\
&= 0,00355 \text{ kg/detik} \\
\rho &= 1,2 \text{ kg/m}^3 \\
A₁ &= \pi/4 \times 0,11 \times 0,11 = 0,0095 \\
A₂ &= \pi/4 \times 0,06 \times 0,06 = 0,0028
\end{align*}
\]

Sehingga,
\[
v = \frac{0,00355}{1,2 \times \frac{\text{kg}}{\text{detik}} \times (0,0095 - 0,0028) \text{ m}^2} = 0,441 \text{ m/s}
\]
Dari hasil pengujian pembakaran limbah serutan kayu sengon sebanyak 1300 gram sampai habis terbakar membutuhkan waktu selama 35 menit. Kecepatan yang harus gunakan untuk terjadinya pembakaran sempurna adalah dengan menambahkan kecepatan udara sebesar 0,441 m/s. Namun dengan kecepatan demikian proses pembakaran didalam tidak terjadi karena aliran udara didalam tidak beraturan dan banyak oksigen yang tidak terealisasikan. Untuk mengatasinya adalah dengan menambah kecepatan udara masuk dengan tujuan dapat mengganti oksigen yang tidak dapat bereaksi. kemudian dilakukan percobaan penyalaan gas dari 0,5 m/s sampai dengan 1,5 m/s yang ditujuan untuk mengetahui pada kecepatan berapa saja kompor menyala stabil. Dari sepuluh pengujian kecepatan di dapatkan 3 kecepatan dengan nyala api paling stabil yaitu pada kecepatan 0,7 m/s, 0,9 m/s dan 1,05 m/s, ketiga kecepatan tersebut yang di jadikan variasi dalam pengambilan data.

D. Komponen Hasil Gasifikasi

Komponen hasil gasifikasi yang didapatkan meliputi gas, arang, dan abu. Adapun untuk kandungan (yield) dari gas, arang, dan abu adalah perbandingan antara massa daripada komponen dibagi dengan massa total (massa bahan bakar + massa udara).

\[
Yield = \frac{\text{Banyaknya komponen}}{\text{Massa udara + massa bahan bakar}}
\]

Dimana massa (m) udara diperoleh dari laju aliran massa udara dikali dengan lamanya waktu pengujian.

\[
m_{\text{udara}} = \dot{m} \times t = (\rho \times V \times A) \times t
\]

\[
= 1,2 \text{ kg/m}^3 \times 0,7 \text{ m/s} \times 0,00628 \text{ m}^2 \times 600 \text{ s}
\]

\[
m_{\text{udara}} = 3,16512 \text{ kg}
\]

\[
= 3165,12 \text{ gram}
\]
(Perhitungan variasi kecepatan 0,7 m/s)

\[ m_{\text{gas}} = m_{\text{bb}} - m_{\text{arang}} - m_{\text{abu}} \]

\[ m_{\text{arang}} = 566,0 \text{ gram} \]
\[ m_{\text{abu}} = 76,0 \text{ gram} \]
\[ m_{\text{bb}} = 1300 \text{ gram} \]

\[
\text{Yield gas} = \left( \frac{m_{\text{gas}} + m_{\text{udara}}}{m_{\text{udara}} + m_{\text{bb}}} \right) \times 100\% = \left( \frac{1300 - 566,0 - 76,0}{1300 + 3165,12} \right) \times 100\% \\
= 85,62 \% 
\]

\[
\text{Yield gas} = \left( \frac{m_{\text{arang}}}{m_{\text{udara}} + m_{\text{bb}}} \right) \times 100\% = \frac{566,0}{1300 + 3165,12} = 12,68 \% 
\]

\[
\text{Yield gas} = \left( \frac{m_{\text{abu}}}{m_{\text{udara}} + m_{\text{bb}}} \right) \times 100\% = \frac{76,0}{1300 + 3165,12} = 1,70 \% 
\]

E. Efisiensi Termal Gasifikasi

Belonio (2005) mengungkapkan bahwa efisiensi termal adalah perbandingan antara energi yang terpakai pada saat mendidihkan dan menguapkan air dengan energi kalor yang tersedia pada bahan bakar. Rumus untuk menghitung efisiensi termal adalah sebagai berikut:

\[
\text{ET} = \text{ET} = \frac{\text{KS} + \text{KL}}{\text{KB}} \times 100\%
\]

Keterangan:

\[ \text{ET} = \text{Efisiensi Termal (}) \%
\]
\[ \text{KS} = \text{Kalor Sensibel (kJ/kg)} \]
\[ \text{KL} = \text{Kalor Laten (kJ/kg)} \]
\[ \text{KB} = \text{Kalor Bahan Bakar (kJ/kg)} \]
1. **Kalor Sensibel** ($Q_{1,2}$)

Diketahui: (data pada variasi udara masuk 0,7 m/s tanpa campuran)

- $T_0 = 27 \, ^\circ C$ (temperatur awal air) \quad $m_0 = 1000$ gram (massa awal air)
- $T_1 = 95,2 \, ^\circ C$ (temperatur akhir pada air) \quad $m_1 = 692$ gram (massa akhir air)

Ditanya:

- $h_1 =$ ?
- $h_2 =$ ?
- $Q_{1,2} =$ ?

Jawab:

$h_1 =$ ? → $T_0 = 27 \, ^\circ C$ → $h_f$

- $T' = 25 \, ^\circ C$ → $h' = 104,83$ kJ/kg
- $T'' = 30 \, ^\circ C$ → $h'' = 125,74$ kJ/kg

Entalpi 1 ($h_1$) didapat dengan cara interpolasi sebagai berikut:

$$\frac{T_0-T'}{T''-T'} \cdot \frac{h_1-h'}{h''-h'} \rightarrow \frac{27 - 25}{30 - 25} = \frac{h_1 - 104,83}{125,74 - 104,83}$$

$h_1 = 113,19$ kJ/kg

$h_2 =$ ? → $T_1 = 95,2 \, ^\circ C$ → $h_f$

- $T' = 95 \, ^\circ C$ → $h' = 398,09$ kJ/kg
- $T'' = 100 \, ^\circ C$ → $h'' = 419,17$ kJ/kg

Entalpi 2 ($h_2$) didapat dengan cara interpolasi sebagai berikut:

$$\frac{T_1-T'}{T''-T'} \cdot \frac{h_1-h'}{h''-h'} \rightarrow \frac{95,2 - 95}{100 - 95} = \frac{h_2 - 398,09}{419,17 - 398,09}$$

$h_2 = 398,93$ kJ/kg

Sehingga kalor sensibel didapatkan dengan rumus:

$Q_{1,2} = m_0 \cdot (h_2 - h_1)$

$Q_{1,2} = 1 \text{ kg} \cdot (398,94 - 113,19)$ kJ/kg

$Q_{1,2} = 285,74$ kJ
2. Kalor Laten (Q\textsubscript{2-3})

Diketahui : (data pada variasi udara masuk 0,7 m/s tanpa campuran)
\[ T_0 = 27 \, ^\circ\text{C} \quad \text{(temperatur awal air)} \quad m_0 = 1000 \, \text{gram} \quad \text{(massa awal air)} \]
\[ T_1 = 95,2 \, ^\circ\text{C} \quad \text{(temperatur akhir pada air)} \quad m_1 = 692 \, \text{gram} \quad \text{( massa akhir air)} \]

Ditanya :
\[ h_3 = ? \]
\[ Q_{2-3} = ? \]

Jawab :
\[ h_3 = ? \rightarrow T = 95,2 \, ^\circ\text{C} \rightarrow h_{fg} \]
\[ T' = 95 \, ^\circ\text{C} \rightarrow h' = 2269,6 \, \text{kJ/kg} \]
\[ T'' = 100 \, ^\circ\text{C} \rightarrow h'' = 2256,4 \, \text{kJ/kg} \]
\[ \frac{T - T'}{T'' - T'} = h_1 - h' \quad \frac{95,2 - 95}{100 - 95} = \frac{h_3 - 2269,6}{2256,4 - 2269,6} \]
\[ h_2s = 2269,1 \, \text{kJ/kg} \]
\[ x = \frac{m_{uap}}{m_{awal}} = \frac{m_{awal} - m_{akhir}}{m_{awal}} = \frac{1000 \, \text{gram} - 691,5 \, \text{gram}}{1000 \, \text{gram}} = 0,3085 \]
\[ x = 0,31 \]
\[ h_3 = h_2 + (x \cdot h_{2s}) \]
\[ h_3 = 398,93 \, \text{kJ/kg} + (0,31 \cdot 2269,1) \, \text{kJ/kg} \]
\[ h_3 = 1098,9 \, \text{kJ/kg} \]

Sehingga kalor laten didapatkan dengan rumus :
\[ Q_{2-3} = m_0 \cdot (h_3 - h_2) \]
\[ Q_{2-3} = 1 \, \text{kg} \cdot (1098,9 - 398,93) \, \text{kJ/kg} \]
\[ Q_{2-3} = 700,01 \, \text{kJ} \]

(Perhitungan variasi kecepatan udara 0,7 m/s)

Diketahui :
\[ KS = 285,74 \, \text{kJ/kg} \]
\[ KL = 700,01 \, \text{kJ/kg} \]
\[ KB = 3496 \, \text{kJ/kg} \]
Sehingga,

\[ ET = \frac{285,74 + 700,01}{3496} \times 100\% \]

ET = 28,2 \% 

**Lampiran 17** Gambar nyala api pada variasi kecepatan udara masuk 0,7 m/s
Lampiran 18 Gambar nyala api pada variasi kecepatan udara masuk 0,9 m/s

Lampiran 19 Gambar nyala api pada variasi kecepatan udara masuk 1,05 m/s
**Lampiran 20** Gambar nyala api pada variasi campuran 25% arang kayu

**Lampiran 21** Gambar nyala api pada variasi campuran 50% arang kayu
**Lampiran 22** Gambar nyala api pada variasi campuran 75% arang

**Lampiran 23** Gambar nyala api pada variasi campuran 100% arang kayu
## TABLE A-4

Saturated water—Temperature table

<table>
<thead>
<tr>
<th>Temp., press., T °C</th>
<th>Specific volume, m³/kg</th>
<th>Internal energy, kJ/kg</th>
<th>Enthalpy, kJ/kg</th>
<th>Entropy, kJ/kg·K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sat. press., P_sat kPa</td>
<td>Sat. liqud. v_l</td>
<td>Sat. Evap. v_e</td>
<td>Sat. Evap. h_e</td>
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