CPPC: Development of a Simple Computer Code for $\text{H}_2$ and CO Combustion in Severe Accidents

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What is CPPC?

• Developed by Polytechnic University of Madrid for CSN.
• Stand-alone code for fast calculations on pressure rises in the containment from \( \text{H}_2 \) and CO combustion in severe accidents.
• Most recent advances in the field of \( \text{H}_2 \) and CO combustion.
• Useful tool for PSA-2 assessments.
What is CPPC?

**INPUT:**
- Masses of $\text{H}_2$ and CO.
- Initial environmental conditions in the containment, before burning.
- Simple geometric data: volume of the enclosure.

**OUTPUT:**
- Combustion completeness.
- Adiabatic and isochoric combustion pressure.
- Chapman-Jouguet pressure.
- Chapman-Jouguet reflected pressure.
- Effective pressure.
- Combustion regime.
Main Assumptions

- Ideal gases.
- Gases homogeneously mixed in containment.
- Steam-saturated atmosphere previous to the combustion.
- Water properties from Steam Tables.
• Correlation for upward propagation:

\[ X_{H2O} = a_f + b_f X_{H2} + c_f \exp \left( d_f X_{H2} + b_f T_u \right) \]

• \( a_f, b_f, c_f, d_f \) fitted experimentally.
Combustion Completeness

- Pilch et al. (1996).
- Murata et al. (1997), taken from CONTAIN 2.0
- HECTR 1.5, taken from MELCOR 1.8.4 (Gauntt, 1997).
Combustion Completeness

- Pilch (XD=0.0)
- Pilch (XD=0.3)
- Pilch (XD=0.6)
- Pilch Spray (XD=0.0)
- Pilch Spray (XD=0.3)
- Pilch Spray (XD=0.6)
- Murata
- Murata Spray
- Gauntt

Molar fraction of flammable gases $X_C$
Combustion Regimes

- Regimes considered:
  - Slow deflagrations
  - Flame Acceleration
  - DDT
  - Detonation

- For each gas mixture CPPC calculates:
  - Fulfillment of criterion for combustion regime.
  - Effective static pressure.
Combustion Regimes (Kuznetsov, 2003).

![Graph showing combustion regimes with different fuel mixtures and flame propagation speeds.](image-url)
Flame Acceleration Criterion

- Selection of parameter ($\sigma$)

\[ \sigma = \frac{v_b}{v_u} = \frac{\rho_u}{\rho_b} \]

- Establishing of $\sigma$ critical

\[ \sigma^* = a_\sigma + b_\sigma \left( \frac{E_a}{T_u} \right)^{c_\sigma} \]
Flame Acceleration Criterion

- Definition of index for FA.

\[ i_\sigma = \frac{\sigma}{\sigma^*} \geq 0.92 \]

- Quantification of index for FA
Flame Acceleration Criterion.
Dorofeev (2001)
DDT Criterion

- Definition of DDT index
- D geometric value
- $\lambda$: detonation cell size
- Quantification of DDT index

\[
i_{\lambda} = \frac{D}{7 \lambda}
\]

\[
D = V^{1/3}
\]

\[
\log_{10}(\lambda) = f(X_{H2,dry}, X_{H2O}, T, p)
\]

\[
i_{\lambda} = \frac{D}{7 \lambda} \geq 0.57
\]
DDT Criterion (CSNI SOAR, 2000).
DDT Criterion (Breitung, 2000).
Direct Detonation Criterion

The diagram illustrates the direct detonation criterion of a mixture of hydrogen ($\text{H}_2$), air, and steam. The boundary lines separate regions of non-flammable, flammable, and detonable mixtures. The stoichiometric mixture of hydrogen and air is within the flammable region.
Pressure Rise Calculation: Slow Deflagrations

\[ \sum_A \left( n_A c_{v,A} \right)_b T_b^{AICC} = \sum_A \left( n_A c_{v,A} \right)_u T_u + n_{H2,q} q_{H2} + n_{CO,q} q_{CO} \]

\[ c_{vA} = \left( A_A + B_A T + C_A T^2 + D_A T^3 \right) \frac{R}{PM_A} - R \]

\[ p_b^{AICC} = p_u \left( \frac{T_b^{AICC}}{T_u} \right) \left( \frac{n_b}{n_u} \right) \]
Pressure Rise Calculation: General Case

\[ y'' + (2 \pi f)^2 y = \frac{p_i(t)}{m} \]

Frequency: input data. 5 to 500 Hz as indicated by Breitung and Redlinger (1995b)
Pressure Rise Calculation: General Case.

- Pi(t) obtained from typical shape of pressure loads at the different combustion regimes (Breitung and Redlinger (1995b)).

- Upper bound values:
  - $P_{CJ} = 1.8 (+0.08) P_{AICC}$
  - $P_{CJ-R} = 4.1 (+ 0.3) P_{AICC}$
Pressure Rise Calculation: General case.
Pressure Rise Calculation:
General case.

- Calculation of the effective static pressure:

\[ y'' + \left(2\pi f\right)^2 y = \frac{p_i(t)}{m} \]

\[ p_{eff} = \left(2\pi f\right)^2 m y_{max} \]
Pressure Rise Calculation: General Case.
Validation & Verification

- Comparison with MELCOR calculations to verify that CPPC provides an upper bound.
- CPPC code uses combustion completeness $\times = 1$.
- T0: scenarios with CHR activation coincident with vessel failure.
- T1: scenarios with CHR activation coincident with the maximum of the $\sigma$ parameter.
- ESF: Spray + Fan-cooling units.
- FCL: Fan-cooling units. Full capacity.
### Validation & Verification

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Duration (s)</th>
<th>H2 (CO) mass burnt (kg)</th>
<th>Pmax (bar)</th>
<th>PAICC (bar)</th>
<th>Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>dryT0-ESF</td>
<td>70</td>
<td>51 (229)</td>
<td>1.69</td>
<td>4.110</td>
<td>SD</td>
</tr>
<tr>
<td>dryT0-FCL</td>
<td>58</td>
<td>80 (331)</td>
<td>1.96</td>
<td>4.106</td>
<td>SD</td>
</tr>
<tr>
<td>dryT0-SPR</td>
<td>31</td>
<td>120 (1175)</td>
<td>2.23</td>
<td>3.996</td>
<td>SD</td>
</tr>
<tr>
<td>wetT0-ESF</td>
<td>57</td>
<td>424 (3145)</td>
<td>5.11</td>
<td>6.483</td>
<td>FA</td>
</tr>
<tr>
<td>wetT0-FCL</td>
<td>57</td>
<td>424 (3149)</td>
<td>5.11</td>
<td>6.495</td>
<td>FA</td>
</tr>
<tr>
<td>wetT0-SPR</td>
<td>17</td>
<td>374 (1914)</td>
<td>4.45</td>
<td>5.175</td>
<td>SD</td>
</tr>
</tbody>
</table>
## Validation & Verification

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Duration (s)</th>
<th>H$_2$ (CO) mass burnt (kg)</th>
<th>P$_{max}$ (bar)</th>
<th>P$_{AICC}$ (bar)</th>
<th>Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>dryT1-ESF</td>
<td>46</td>
<td>364 (2848)</td>
<td>4.53</td>
<td>5.322</td>
<td>FA</td>
</tr>
<tr>
<td>dryT1-FCL</td>
<td>58</td>
<td>361 (2644)</td>
<td>4.46</td>
<td>5.332</td>
<td>FA</td>
</tr>
<tr>
<td>dryT1-SPR</td>
<td>44</td>
<td>360 (2635)</td>
<td>4.46</td>
<td>5.378</td>
<td>FA</td>
</tr>
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<td>wetT1-ESF</td>
<td>88</td>
<td>420 (3138)</td>
<td>5.07</td>
<td>6.374</td>
<td>FA</td>
</tr>
<tr>
<td>wetT1-FCL</td>
<td>86</td>
<td>422 (3155)</td>
<td>5.07</td>
<td>6.375</td>
<td>FA</td>
</tr>
<tr>
<td>wetT1-SPR</td>
<td>89</td>
<td>419 (3129)</td>
<td>4.92</td>
<td>6.453</td>
<td>SD</td>
</tr>
</tbody>
</table>
Validation & Verification

- CPPC results compared with those obtained with other code for AICC calculations in case of slow deflagrations.

- Satisfactory results, differences in the pressure increase range in the 1%.
Validation & Verification. Breitung calculations.

<table>
<thead>
<tr>
<th>XH2 (% vol)</th>
<th>XH2O (% vol)</th>
<th>Tu (*) (K)</th>
<th>Pu (*) (bar)</th>
<th>$P_{AICC}$ Breitung (bar)</th>
<th>$P_{AICC}$ CPPC (bar)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>30</td>
<td>362</td>
<td>2.26</td>
<td>9.953</td>
<td>10.03</td>
<td>-0.8</td>
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<tr>
<td>20</td>
<td>40</td>
<td>380</td>
<td>3.26</td>
<td>14.48</td>
<td>14.4</td>
<td>0.6</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>366</td>
<td>2.58</td>
<td>13.29</td>
<td>13.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>335</td>
<td>1.62</td>
<td>7.487</td>
<td>7.95</td>
<td>-1.3</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>293</td>
<td>1.27</td>
<td>8.618</td>
<td>8.82</td>
<td>-2.3</td>
</tr>
<tr>
<td>29.5</td>
<td>0</td>
<td>293</td>
<td>1.44</td>
<td>11.87</td>
<td>12.77</td>
<td>-7.5</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>342</td>
<td>2.12</td>
<td>13.31</td>
<td>13.36</td>
<td>-0.3</td>
</tr>
<tr>
<td>25</td>
<td>30</td>
<td>368</td>
<td>2.84</td>
<td>14.28</td>
<td>14.24</td>
<td>0.3</td>
</tr>
</tbody>
</table>
• Relative errors lie around 1% in wet mixtures.

• Less than 10% in dry mixtures.

• Results are considered as acceptable.
CSN methodology to calculate the containment failure probability due to hydrogen combustion during the in-vessel phase
Plant Applications

- Obtain containment pressure prior to $H_2$ combustion. MELCOR calculations.
- Obtain $H_2$ mass in the containment. $H_2$ well mixed.
- Calculate the containment pressurization. CPPC useful in this step.
- Overlap the containment pressure distribution with containment fragility curve to obtain containment failure probability.
- Reflooding considered: 20% additional hydrogen generation (Kuan, 1994).
Plant Applications

![Graph showing probability distribution of Zr fraction oxidized](image)
Plant Applications

**Results obtained**

- No reflooding scenarios: negligible probability.
- Reflooding scenarios: significant increase in the containment failure probability and potential for flame acceleration.
- Safety significance of these results under study.
Plant Applications: No reflooding case

CUMULATIVE PROBABILITY

PRESSURE (BARS)

FRAGILITY
1.39 BARS
Plant Applications

• Future applications are planned:

  • Continuation of the verification process.

  • Calculation of the containment failure probability for the ex-vessel phase.

  • Analyses of local hydrogen accumulations.