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Modelling Small-scale CHP Plant Under Closed Loop Control

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**Background – UK Climate Change Levy**

- A commodities tax introduced in April 2001
- Applicable to electricity, gas and other fuels (but not oil since this is already subject to excise duty)
- Payable by most (there are a few exceptions) non-domestic energy consumers
- Examples of current Levy rates: 0.15 p/kWh (natural gas); 0.43 p/kWh (electricity)
Purpose of the Levy: to help secure the UK’s CO₂ emissions reduction target (5% (Kyoto-binding); 12.5% targeted by between 2008 – 2012)

Fuels used in “good quality” CHP will be exempt from the Levy

UK CHP capacity target of 10 GWe by 2010 (about 15% of current capacity)
CHP Quality Indexing

- Quality indexing scheme operated by the CHPQA group at the UK’s DEFRA
- $QI$ thresholds set for different types of CHP installation
- A $QI$ is calculated as a weighting of power and heat from CHP that is actually utilised
- Example, for small scale installations < 1 MWe...

Threshold: $\eta \geq 0.2$ AND $QI \geq 115$

Where: $QI = 230\eta + 125\phi$
($\eta = \text{efficiency}; \phi = \text{heat "efficiency"}$)
Modelling Equations – Gas and Work

\[
\eta_{\text{indicated}} = 1 - r_c^{1-\gamma}
\]

\[
V = V_{\text{disp}}
\]

\[
P_3 = \text{fnc}(v_{\text{cyl}}, T_{\text{ai}}, M_f, \eta_{\text{indicated}}, FLHV, W_{\text{brake}})
\]

\[
P_2 = \max(P_3, P_{\text{crit}})
\]

\[
M_g = \text{fnc}(A_{\text{throat}}, v_{\text{ai}}, T_{\text{ai}}, P_2, P_{\text{ai}})
\]

\[
A_{\text{throat}} = \text{fnc}(IV_{\text{lift}}, IV_{\text{diam}})
\]

\[
W_{\text{brake}} = \text{fnc}(M_g, \eta_{\text{indicated}}, \eta_{\text{mech}}, FLHV)
\]

\[
M_f = \text{fnc}(FAR, M_g)
\]

\((M_g \text{ is solved recursively})\)
Modelling Equations – Heat Transfer

\[ T_{\text{adiabatic}} = fnc\left(h_{\text{gas-chamber}}, FLHV, FAR\right) \]

(\( T_{\text{adiabatic}} \) implicit in \( h_{\text{gas-chamber}} \) hence solve recursively)

\[ T_{\text{gas-outlet}} = fnc\left(T_{\text{adiabatic}}, W_{\text{brake}}\right) \]

\[ Q_{\text{HX}} = fnc\left(T_{\text{gas}}, T_{\text{coolant}}, E_{\text{HX}}\right) \]

\[ Q_{\text{loss}} = fnc\left(T_{\text{coolant}}, T_{\text{ambient}}, E_{\text{loss}}\right) \]
Modelling - Uncertainties

- Inlet throat area fitted to mnfrs. data
- General form...

\[ IV_{lift} = C_1 + C_2 V_{disp} + \ldots \]
\[ C_3 V_{disp}^2 + C_4 r_c + \ldots \]
\[ C_5 r_c^2 + C_6 r_c V_{disp} + \ldots \]
\[ C_7 (r_c V_{disp})^2 \]

- Mechanical efficiency balanced from mnfrs. data
- Generally lower for smaller engines
- Typically, for naturally aspirated SI engines up to 250 kW...

\[ 0.6 \leq \eta_{mech} \leq 0.82 \]
Matlab Function - ChpSim

**Parameter Set**
- Number of Cylinders: 4
- Cylinder Bore (mm): 108
- Displacement Volume (all cylinders - litres): 4.58
- Compression Ratio (typically: 10 (SI), 20 (CI)): 10
- Mechanical Efficiency (fraction): 0.65

**Input Data Set**
- Relative Air:Fuel Ratio (Stoichiometric=1): 1
- Jacket Water Mass Flow rate (kg/s): 1
- Jacket Inlet Water Temperature (K): 391.15
- Inlet Air Pressure (Nsq m): 101325
- Inlet Air Temperature (K): 298.15
- Engine Speed (RPS): 25

**Auxilliary HX Size**
- Aux. Heat Exchanger Surface Area (sq m): 5

**Jacket-series, separate circuit or...**
- Auxillary cooling
  - Series
  - Separate
  - None
# Manufacturers Reference Data

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<th>Manufacturer</th>
<th>Model</th>
<th>Brake Power (kW)</th>
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Correlation with Manufacturers Data

- Normalised Brake Power (MODEL) vs. Normalised Brake Power (ACTUAL)
- Brake Efficiency (MODEL) vs. Brake Efficiency (ACTUAL)
- Normalised Heat Recovery (MODEL) vs. Normalised Heat Recovery (ACTUAL)
Parameter Extraction Using ChpSim

Throttling Rate:
$$TR = 0.4262 + 0.59283LF$$

Power Output:
$$P = -128.12 + 367.16TR$$

Heat Recovery:
$$Q = 157 + 135.26TR$$

Brake Efficiency:
$$\eta = -0.22407 + 0.98871TR - 0.42815TR^2$$
Matlab Function ChpScheduler

- Reads hourly time series of heat & power demands
- Performs an hourly balance to give...
  - Module matching
  - Turndown
  - Energy balance
  - Machine utilisation
- Integrated annual energy balance includes $Q_I$
Application Example: 700-household Village

- “Heat-rich” case
- Two scenarios...
  - existing case
  - 50% reduced heating to reflect a major insulation campaign
Simulated Village Energy Demands

Cockfield Village: Predicted Global Domestic Energy Demands
Bold pattern: electricity demand  Feint pattern: heating demand

Hour (Start 01:00 first day of the month)
**Application – Nominal Module Choice**

- Naturally aspirated gas engine
- 8-cylinder in-line; 137 mm bore; 26.9 ltr.; \( r_c = 10 \);
  \( \eta_{\text{mech}} = 0.65 \); \( M_w = 5 \text{ kgs}^{-1} \) (series cooled)
- Parameter extraction from *ChpSim*...

\[
Q_{\text{recovery}} = 0.699 + 0.302 \left( \frac{W}{W_{\text{rated}}} \right)
\]

\[
\eta = 0.0686 + 0.450 \left( \frac{W}{W_{\text{rated}}} \right) - 0.182 \left( \frac{W}{W_{\text{rated}}} \right)^2
\]

- Simulated nominal capacities 239 kWe / 292 kWt
**Results – Efficiency and Module Utilisation**

![Graph showing Power Efficiency and Module Utilisation](image)

- Power efficiency - both cases
- Module utilisation - both cases

Minimum Turndown versus Power Efficiency and Module Utilisation.
Results – Heat Recovery Utilisation

![Graph showing Heat Recovery Utilisation vs Module Turndown]

- Reduced Heat Demand
- Full Heat Demand
Results – Quality Index

Quality Index

- Module Turndown

QI - full heating
QI - reduced heating

Quality Index

Threshold

Results – Quality Index

Module Turndown

QI - full heating
QI - reduced heating

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Conclusions and Further Work

- For maximised $QI$ and $\eta$, a CHP module must be capable of turndown though this will reduce module utilisation.
- The minimum turndown is shown here to maximise $QI$ when set at 0.7 whereas for maximised $\eta$ it should be 0.8 – 0.9.
- For a “heat rich” application, heat recovery utilisation is maximised when no turndown is applied.
- Further work is required to investigate short term module dynamics, smart control and thermal storage.
- Further work is also needed to extend the range of model applicability to large turbo/super-charged engines and gas turbines.