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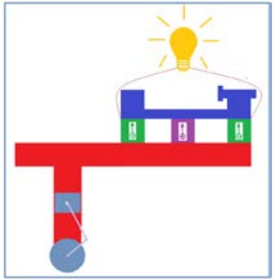
UNDERSTANDING THE OPERATION OF THERMOELECTRIC GENERATORS UNDER TRANSIENT FLOW AND TEMPERATURE CONDITIONS

THERMOELECTRIC NETWORK MEETING

GLASGOW, 18TH OCTOBER 2016

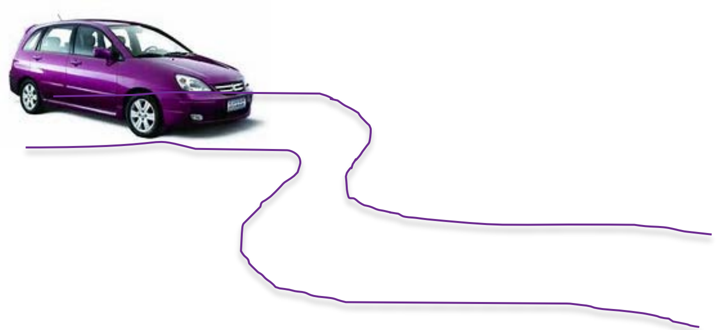
Agenda

- Introduction
- Sources of fluctuation exhaust gas conditions
- Dynamics within TEG
- TEG dynamic modelling methodology
  - i. Thermal network
  - ii. Energy conservation
  - iii. Dynamic TEG model structure
  - iv. Hot side heat exchanger sub model
  - v. Thermoelectric module geometry sub model & design option
- Impact of thermal inertia on TEG performance
- Conclusions
- Future work



1. Sources of fluctuation exhaust gas conditions

Variable road conditions results in wide fluctuating gas flow rate and gas temperature



Vehicle Speed

↓

Engine Speed & Load

↓

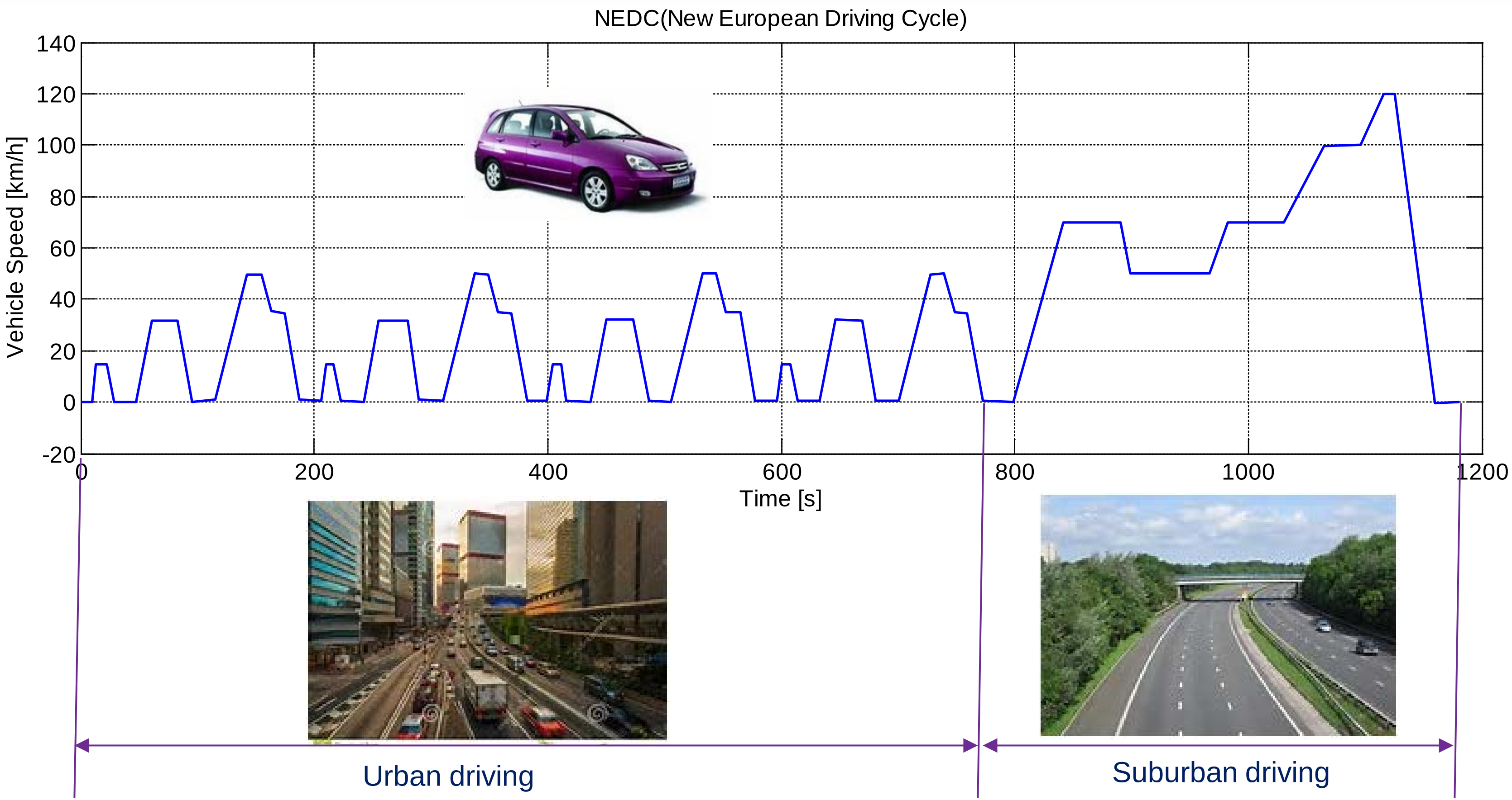
Engine Exhaust Gas Flow Rate & Temperature

↓

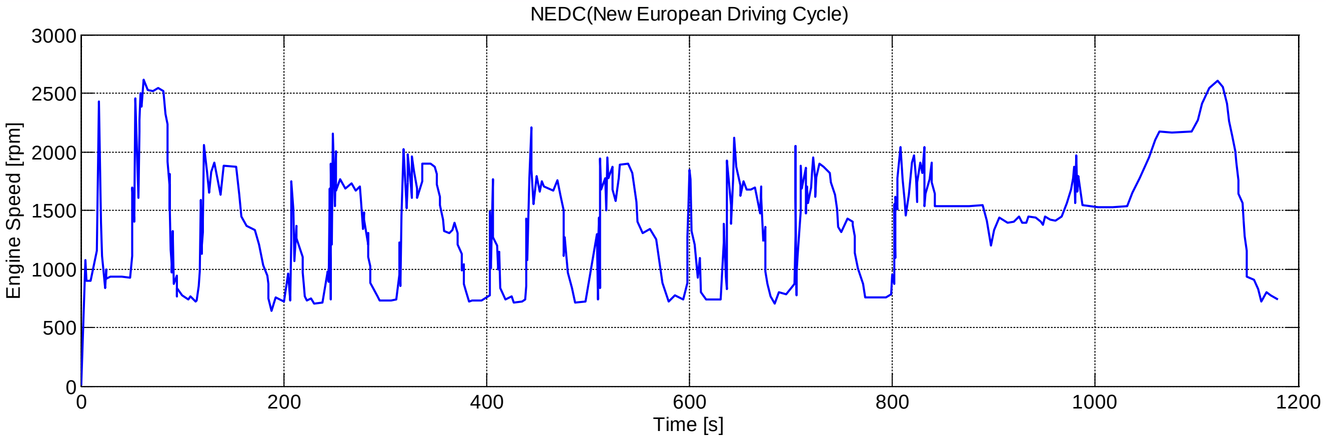
Thermoelectric Generator Output Dynamics

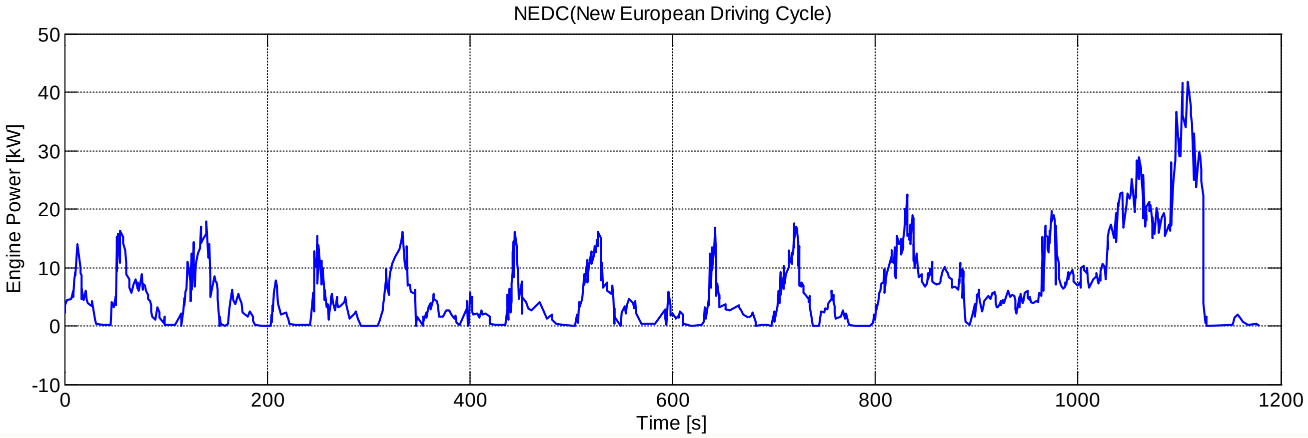
Vehicle control
Transmission control
Engine control
Thermal management

Vehicle driving cycle-NEDC



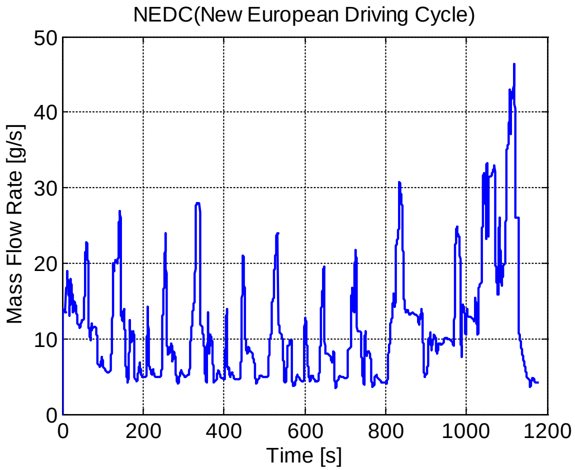
Engine speed and power during NEDC-an example

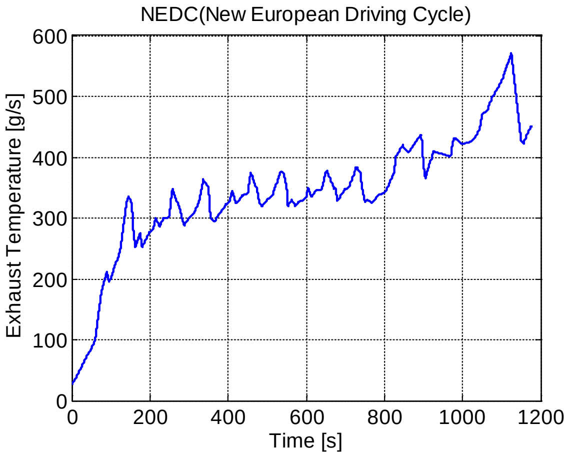


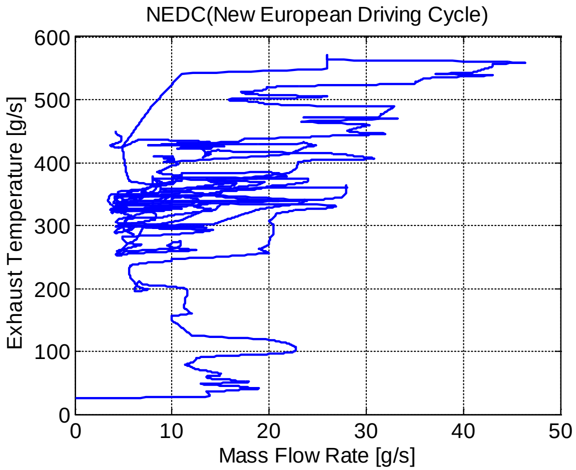


Different type of vehicle and different transmission control will result in different engine transient operating conditions

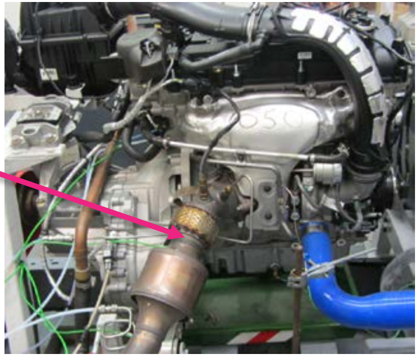
Exhaust gas flow rate and temperature during NEDC







Exhaust path

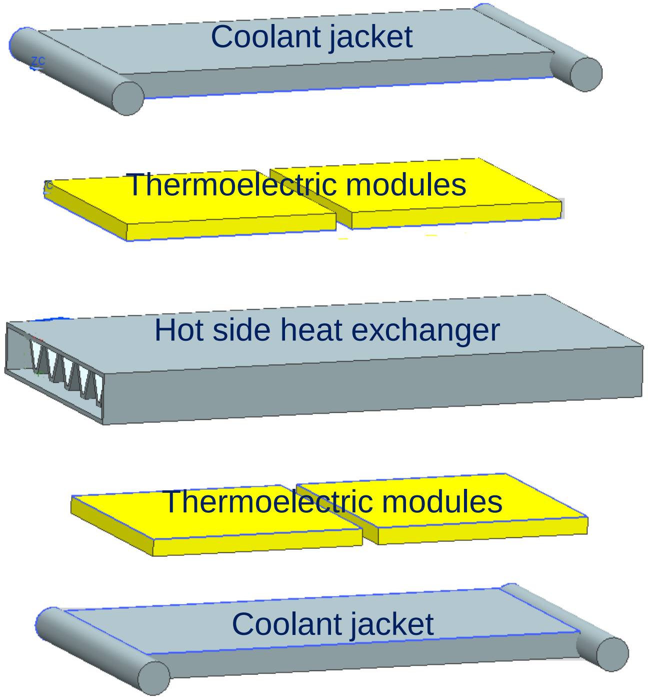


Mass flow rate has faster dynamics than exhaust temperature

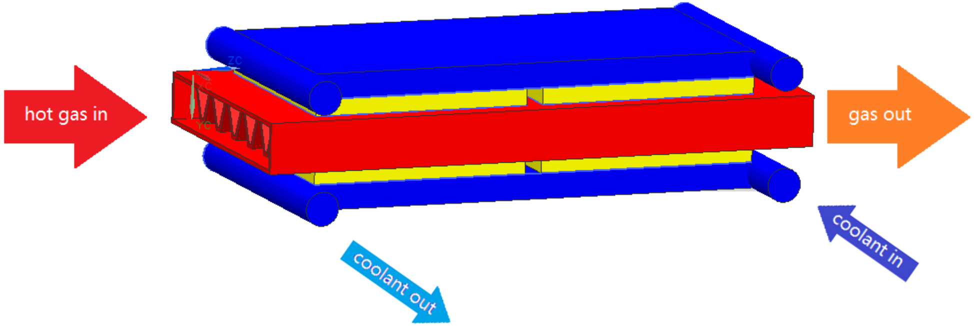
2. Dynamics within TEG

One thermoelectric unit

Elements of one TEG unit



One TEG unit in working form (clamping elements are not displayed)



The impact of transient gas flow and temperature conditions on TEG performance

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1. Exhaust gas and coolant dynamic compressibility
2. Exhaust gas properties change with temperature
3. Inertia of exhaust gas and coolant
4. Thermal Inertia of heat exchanger
5. Dynamic aspects of changing material and transport properties of thermoelectric material
6. Heat exchanger performance varies with input gas conditions
7. Variable thermal expansion results in variable contact thermal resistance
8. MPPT control dynamics
9. Transient pressure drop across TEG has transient influence on engine behaviour via pumping loss and turbocharger

Our TEG dynamic model so far includes: 2, 4, 5, 6

3. TEG dynamic modelling methodology

i. Thermal network
ii. Energy conservation
iii. Dynamic TEG model structure
iv. Hot side heat exchanger sub model
v. Thermoelectric module geometry sub-model & design option

Thermal network model

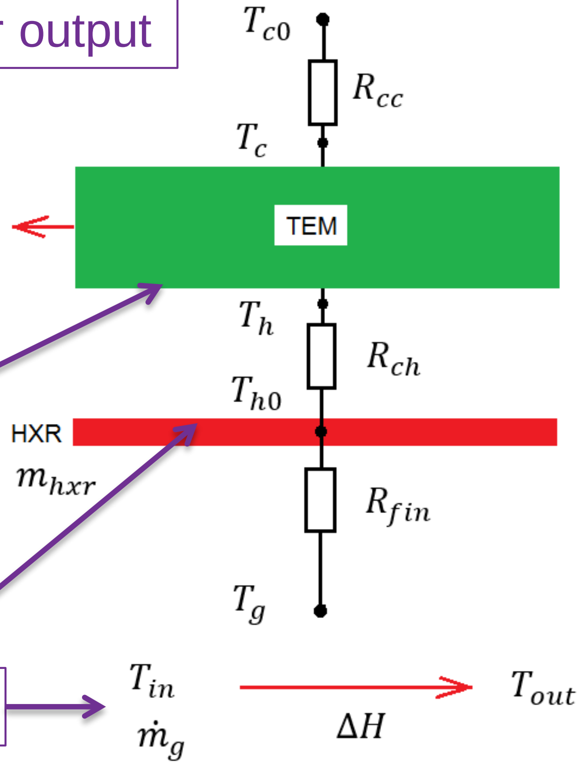
TEG maximum power output

$$P_{max} = \frac{s_{TE}^2 (T_h - T_c)^2}{4 r_{int}}$$

Hot side of the TEM

Heat exchanger surface

Exhaust energy in



Energy to coolant

$$Q_{cc} = \frac{T_{cc} - T_{c0}}{R_{cc}}$$

$$Q_c = s_{TE} T_c I + \frac{1}{2} I^2 r_{int} + k_{TE}(T_h - T_c)$$

$$Q_h = s_{TE} T_h I - \frac{1}{2} I^2 r_{int} + k_{TE}(T_h - T_c)$$

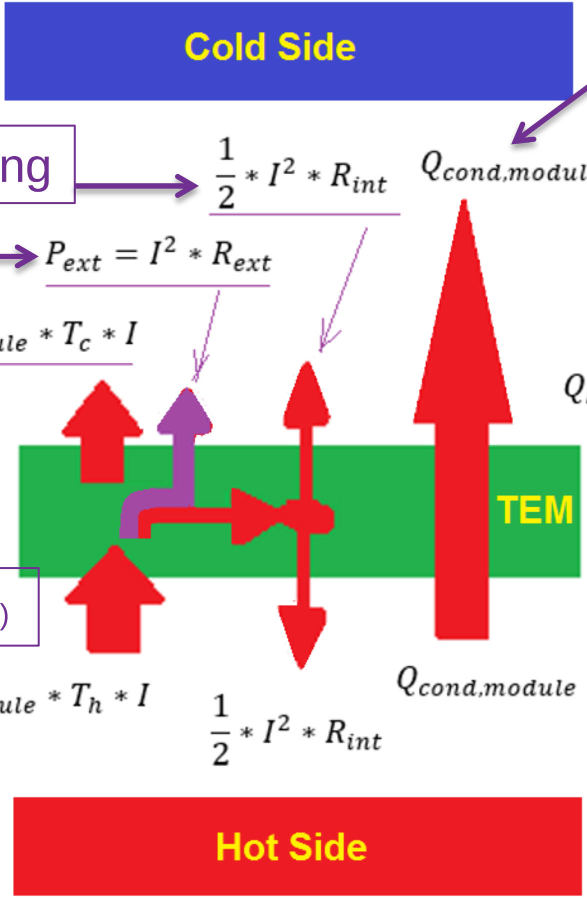
$$Q_{ch} = \frac{T_{h0} - T_h}{R_{ch}}$$

$$Q_{fin} = \frac{T_g - T_{h0}}{R_{fin}}$$

$$\Delta H = \dot{m}_g C_{p,g} (T_{in} - T_{out})$$

Change of enthalpy of the exhaust gas

Thermal energy flow via thermoelectric module



Conduction heat transfer

$$Q_{cond,module} = \frac{T_h - T_c}{R_{module}}$$

Joule heating

$$\frac{1}{2} * I^2 * R_{int}$$

TEG output power

$$P_{ext} = I^2 * R_{ext}$$

Peltier pumping energy (cold side)

$$Q_{peltier,c} = s_{module} * T_c * I$$

Peltier pumping energy (hot side)

$$Q_{peltier,h} = s_{module} * T_h * I$$

$$\frac{1}{2} * I^2 * R_{int}$$

$$Q_{cond,module}$$

$$Q_h = Q_{peltier,h} - \frac{1}{2} * I^2 * R_{int} + Q_{cond,module}$$

$$Q_{peltier,h} - Q_{peltier,c} = P_{elect}$$

$$Q_c = Q_{peltier,c} + \frac{1}{2} * I^2 * R_{int} + Q_{cond,module}$$

$$P_{elect} = P_{int} + P_{ext}$$

$$P_{int} = I^2 * R_{int}$$

Dynamic TEG Model Structure

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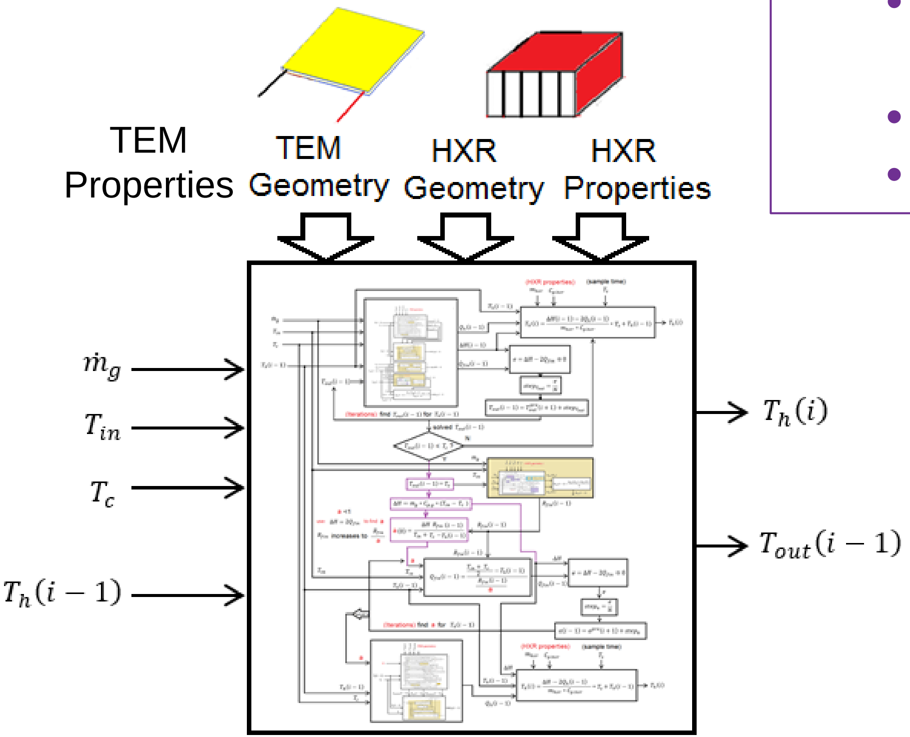

- Rapid design evaluation – including optimal design
- Understanding of cause and effect
- Real time use to support “rapid prototype

A dynamic model made up of many elements – each representing a module

- Represents dynamic aspects of energy transfer
- Is scalable

Hot side heat exchanger performance varies with gas in conditions

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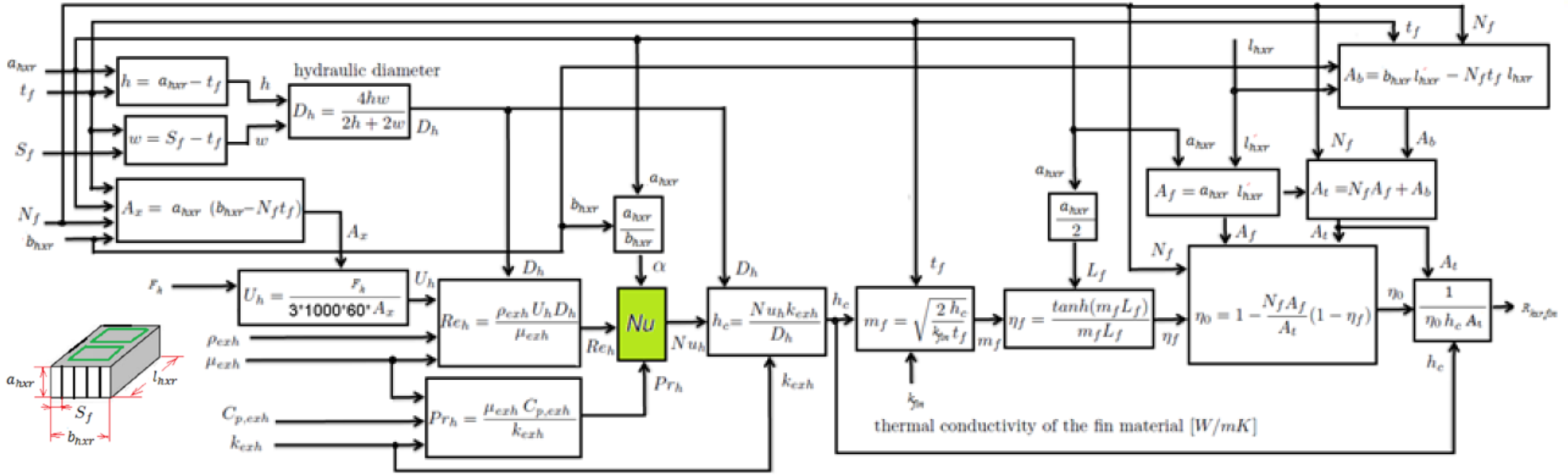
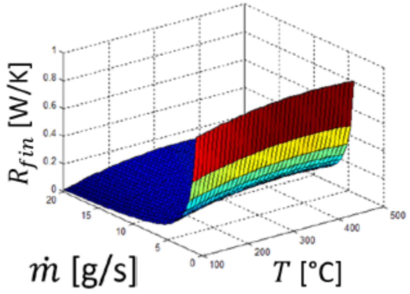


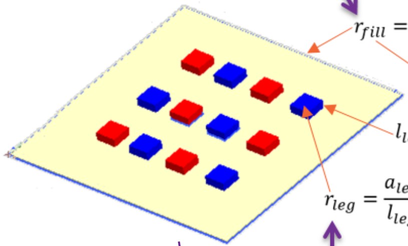
Fin geometry
HXR geometry
Gas flow rate
Gas properties(vary with temp)

→ **Heat exchanger model** →

HXR fin thermal resistance



Thermoelectric module geometry-three design parameters



Fill ratio

$$r_{fill} = \frac{n_{couple} * A_{leg}}{A_{module}}$$

Module ratio

$$r_{module} = \frac{r_{fill}}{l_{leg}}$$

Leg length

l_{leg}

Aspect ratio of leg

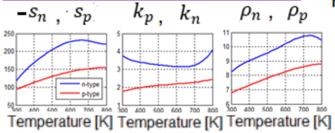
$$r_{leg} = \frac{a_{leg}}{l_{leg}}$$

P

P_{max} has reciprocal relationship to R_{module}

$$P_{max} = \frac{(-s_n + s_p)^2 * (T_h - T_c)^2}{8 * (\rho_n + \rho_p) * (k_{TE} - k_{gap}) + \frac{k_{gap}}{r_{fill}}} * \frac{1}{R_{module}}$$

Skutterudite



Material Parameters

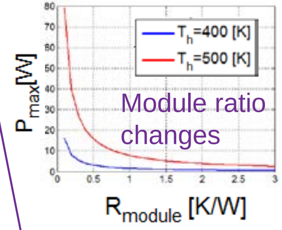
s_n , s_p

ρ_n , ρ_p

k_p , k_n

Hotside and Coldside Temperature

T_h , T_c



Inputs: n_{couple}, l_{leg}, r_{module}, a_{module}, b_{module}

$$r_{fill} = \frac{l_{leg}}{r_{module}}$$

r_{fill}

$$a_{leg} = \sqrt{\frac{a_{module} * b_{module} * r_{fill}}{2 * n_{couple}}}$$

n_{couple}, a_{leg}

$$s_{module} = n_{couple} * (-s_n + s_p)$$

$$V_{ocv} = s_{module} * (T_h - T_c)$$

$$R_{int} = \frac{n_{couple} * l_{leg}}{a_{leg}^2} * (\rho_n + \rho_p)$$

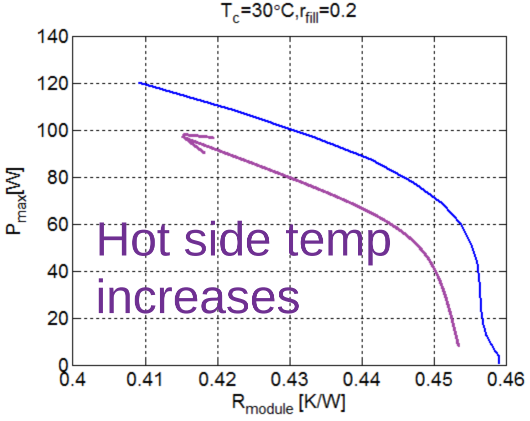
$$P_{max} = \frac{V_{ocv}^2}{4 * R_{int}}$$

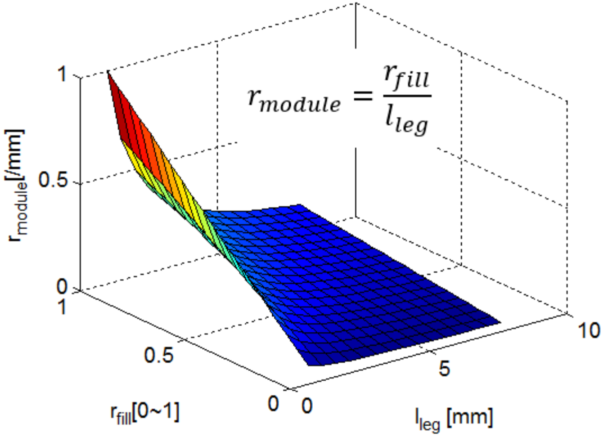
$$k_{module} = k_{TE} * r_{fill} + k_{air} * (1 - r_{fill})$$

$$R_{module} = \frac{l_{leg}}{k_{module} * A_{module}}$$

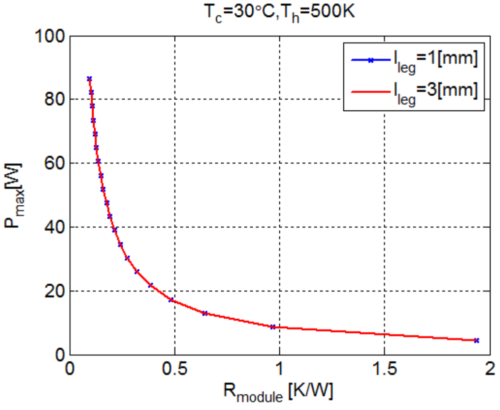
Outputs: P_{max}, R_{module}

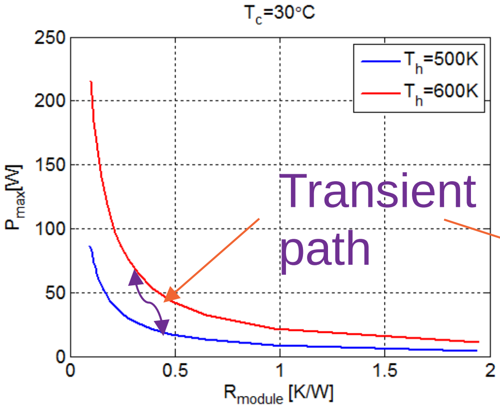
Hot side temperature has impact on the relationship between P_{max} and R_{module}

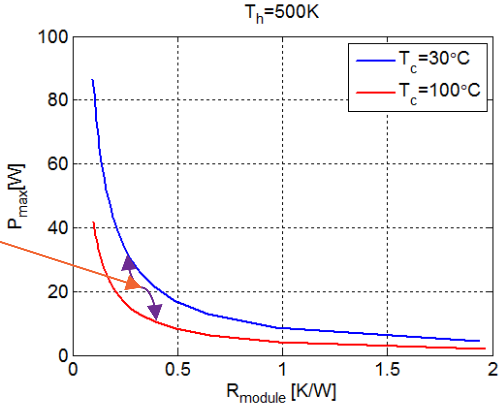




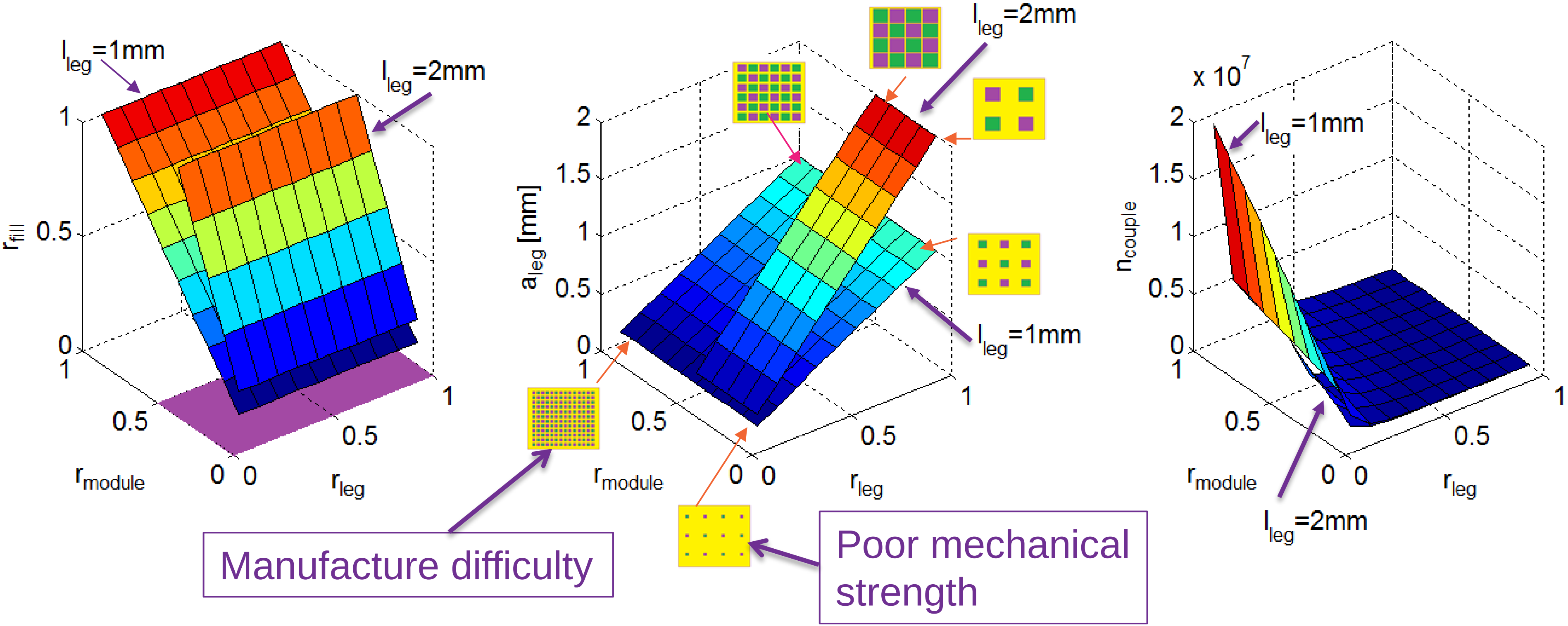
- If module ratio is fixed, leg length has no impact on P_{max} and R_{module}
- Higher T_h or lower T_c result in higher values of both P_{max} and R_{module}. The sensitivity is the same. However, T_h has a larger variation range than T_c







Constraints of leg length on r_{module}, a_{leg} and n_{couple}



The longer the leg length, the smaller maximum r_{module}, the bigger maximum a_{leg}, and the smaller maximum n_{couple}

r_{module} determines the trade-off between P_{max} and R_{module}

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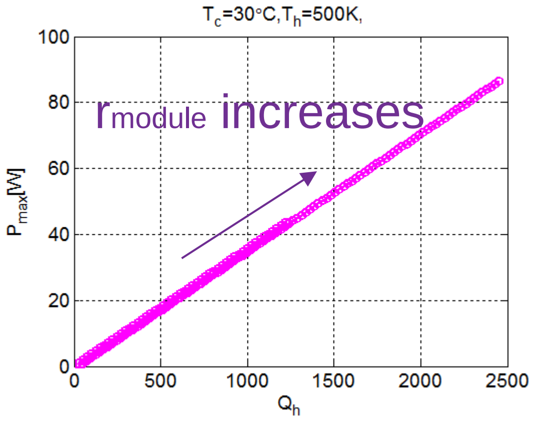
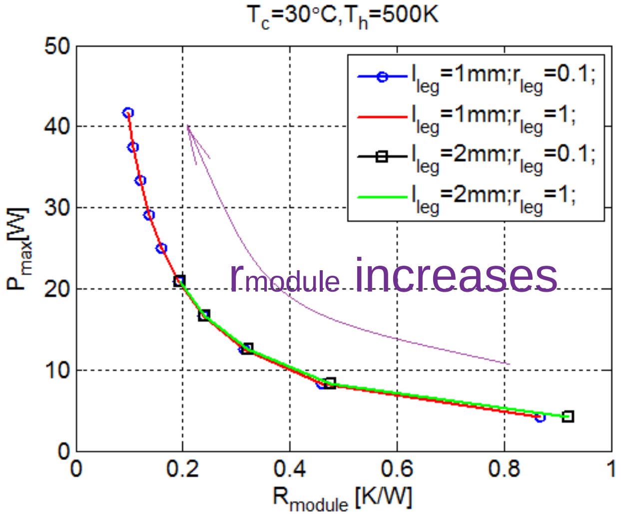


P_{max} is linearly correlated to Q_h: this correlation is not changed by leg length and leg aspect ratio

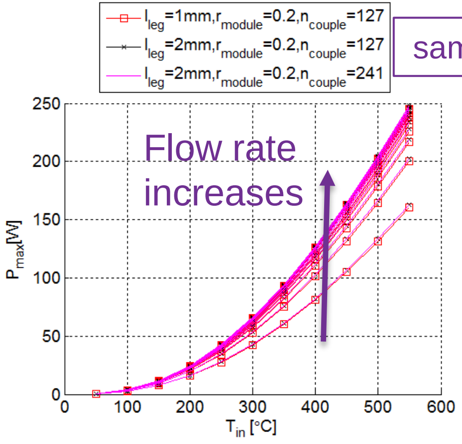


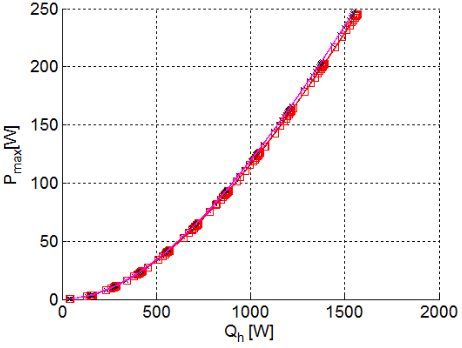
Manufacturability limits the high number of couples and thinness of leg

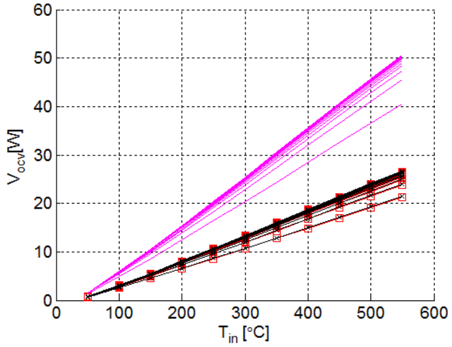
- Different leg length or leg aspect ratio does not change the trade off between maximum power and module thermal resistance
- Lower maximum power for longer leg length

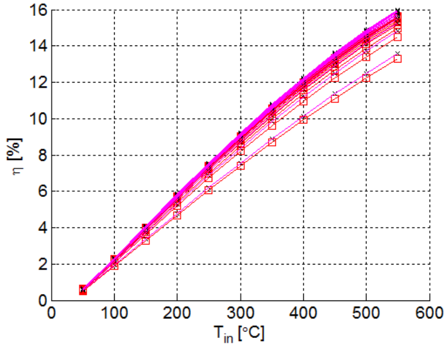
The lower r_{module} the higher efficiency

same r_{module}, different leg length and number of couples=>thermal efficiency has no big difference

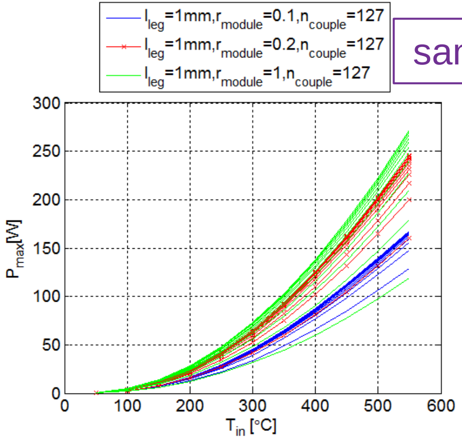


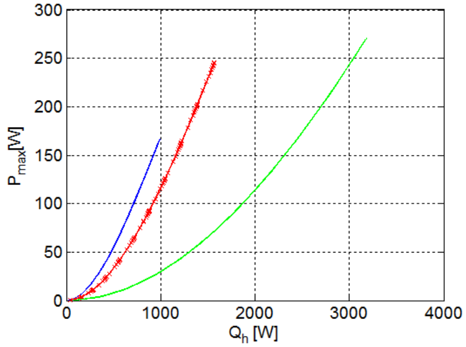


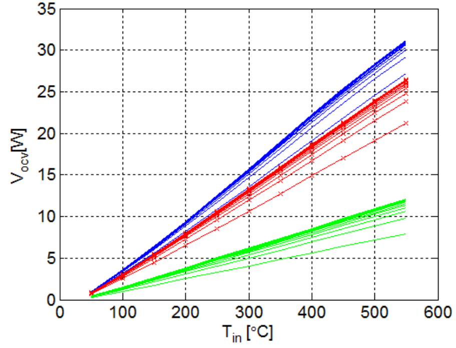


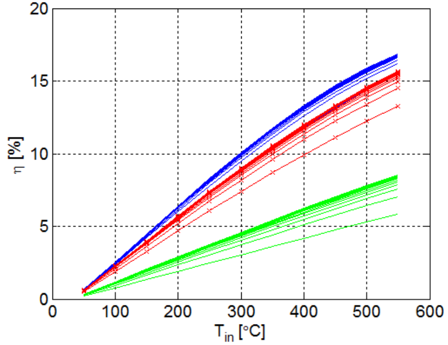


same leg length and number of couples, the lower r_{module}, the higher thermal efficiency

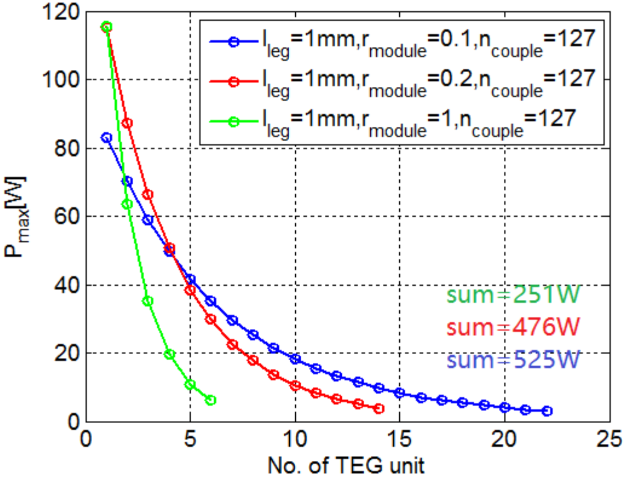


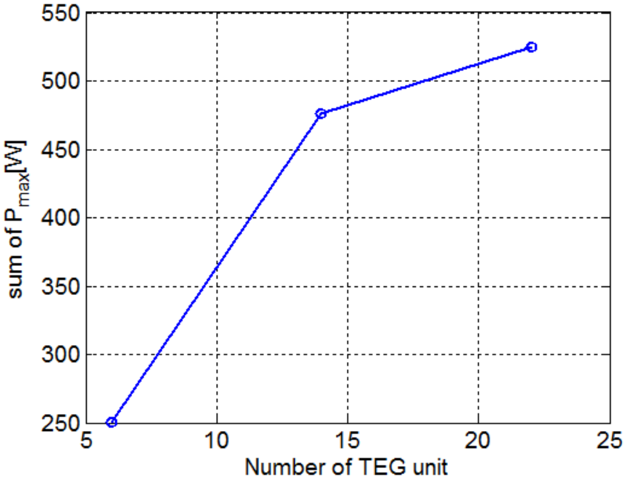


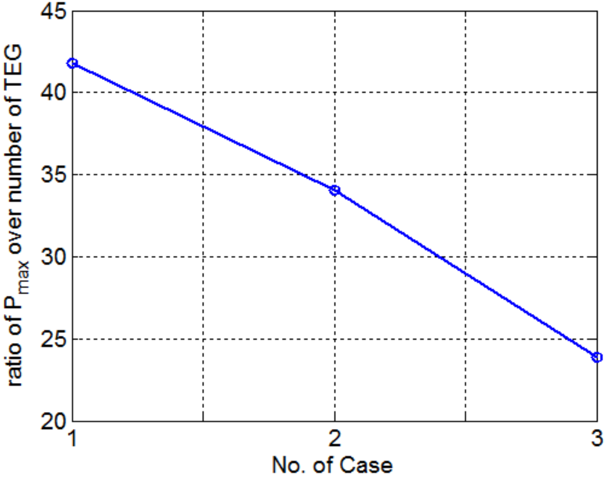




Cost and Size of TEG is an another constraint







- The total thermal efficiency is higher at low r_{module}, however, the ratio of total P_{max} to the number of TEMs is much lower, meaning higher TEG cost
- Lower r_{module} at the same leg length and number of couples implies a lower fill ratio

4. Impact of thermal inertia on TEG performance

i. Validated dynamic TEG model
ii. Predict the impact of thermal inertia on TEG output

Dynamic TEG Model Validation- (NRTC)

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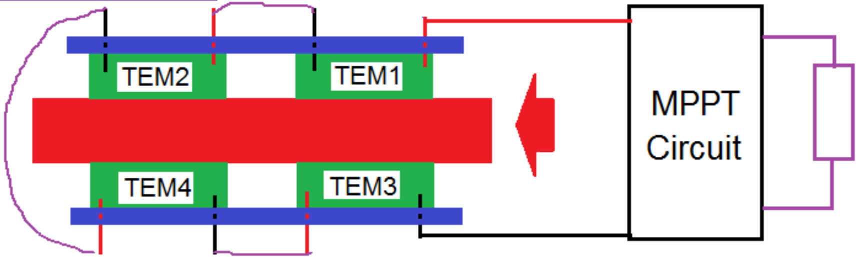
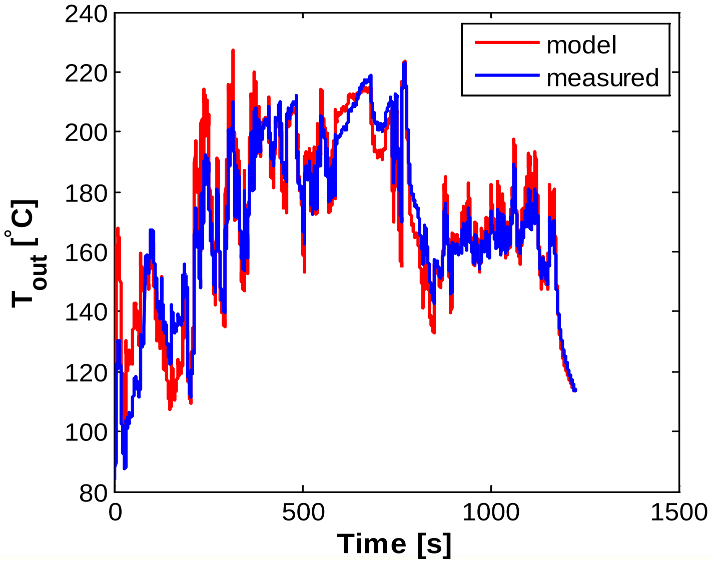
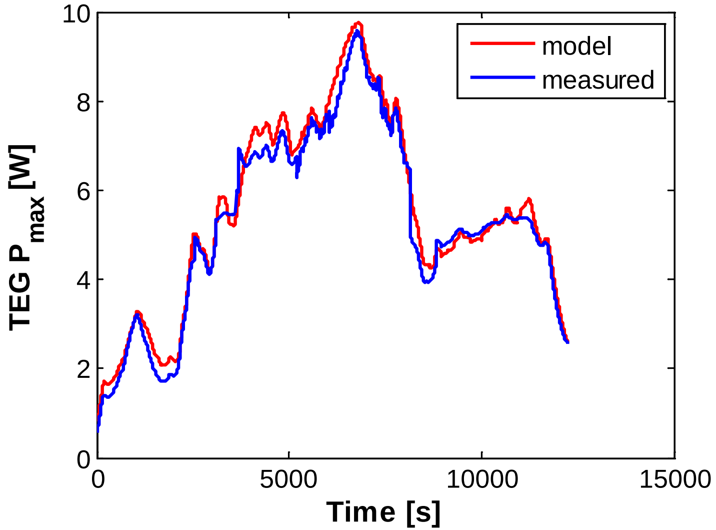
How well do we track dynamic behaviour?

- Gas conditions are the result of transient engine operation
- Maximum power is tracked







TEG output under different thermal inertia condition during NEDC transient cycle

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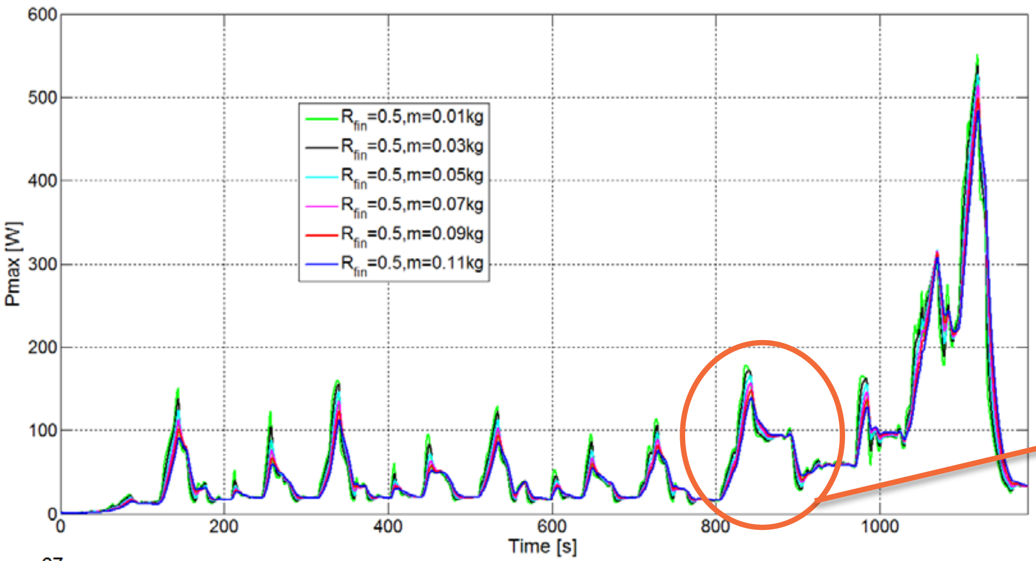

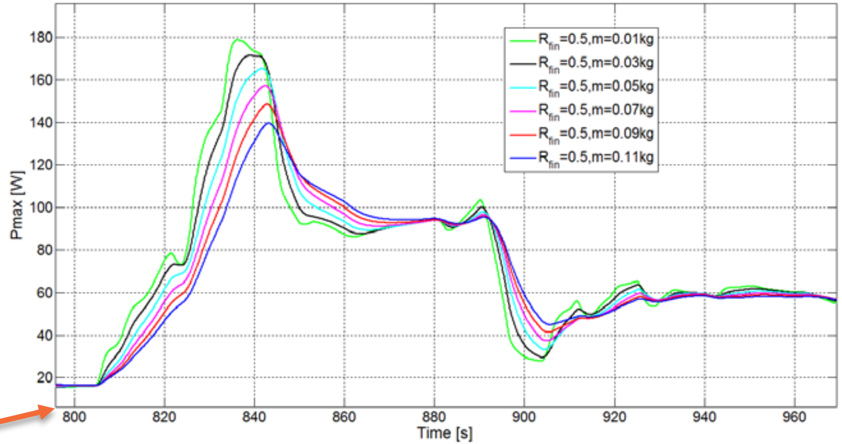

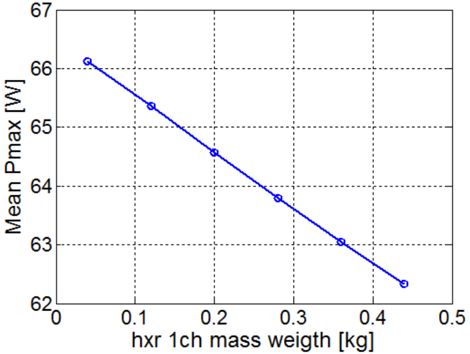

- The greater the mass of hot side heat exchanger, the smaller the spikes caused by the fluctuation of gas-in condition, results in smaller mean P_{max}
- We can use this thermal inertia to suppress transient high temperature and reduce the bypass requirement

Conclusions

1. Road and traffic conditions, driving capability and control systems are the sources for wide fluctuation of exhaust gas conditions
2. Within the TEM, there are also a few factors that have impact on TEG dynamic performance. However thermal inertia, material properties and heat exchanger performance are the key components
3. The dynamic TEG model has good validation result against the engine transient test cycle
4. The thermoelectric module sub-model provides a good guide in the design of module geometry
5. Thermal inertia can be used as a design factor for matching engine exhaust gas transient features to maximize the TEG output

Future work

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1. Include thermal expansion effect in the TEG model and investigate other dynamical process and there contributions to improving model accuracy
2. Modelling the relationship among thermal inertia, heat exchanger performance, pressure drop and bypass function
3. Investigate the influence of TEG on engine behaviour, hence can develop a complete engine-TEG model
4. Develop an optimization algorithm for transient cycle based optimal TEG design

Thank you!

Q&A

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