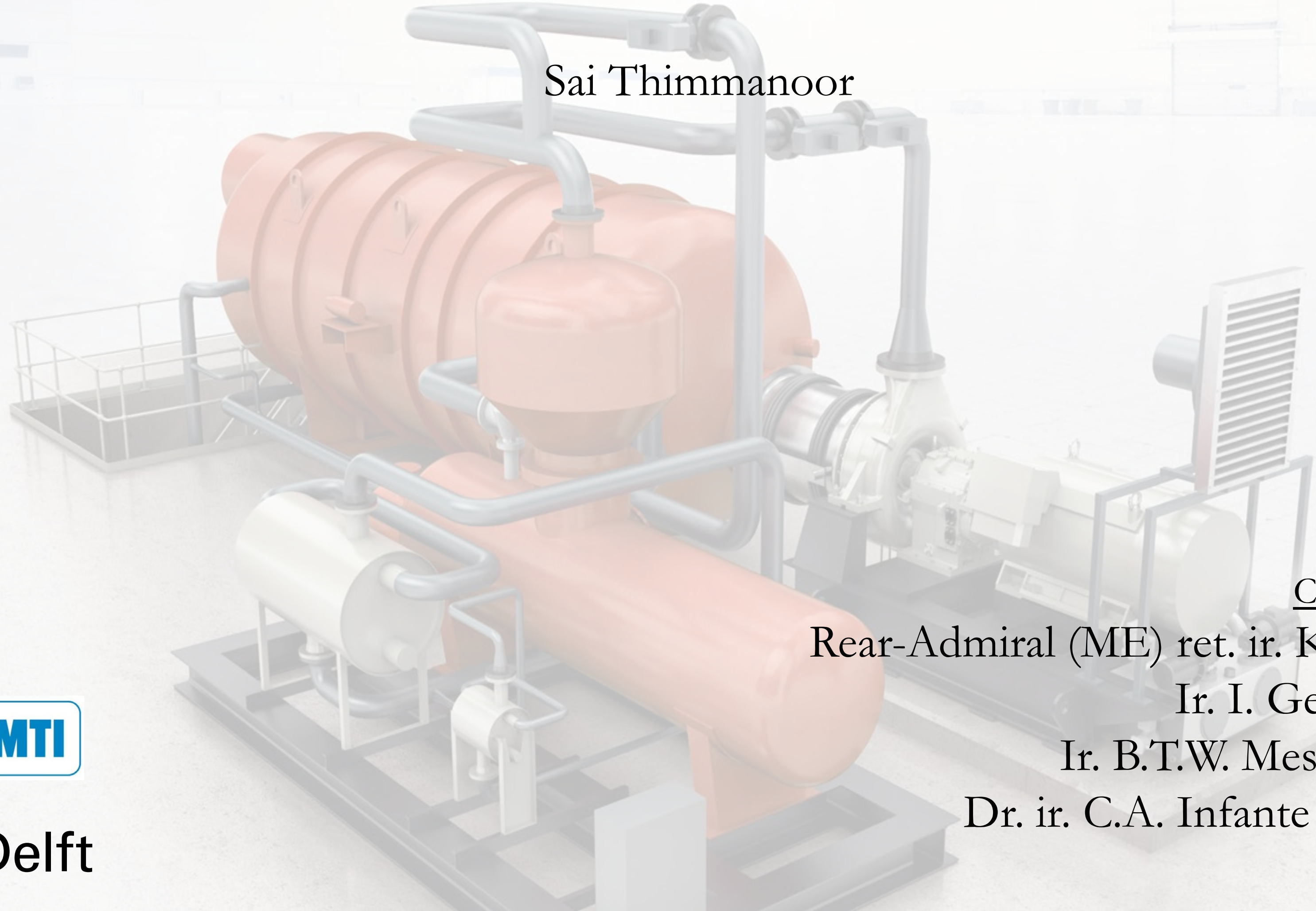
Organic Rankine cycle as waste heat recovery system for marine application

15. Jan. 2018

Sai Thimmanoor



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Content

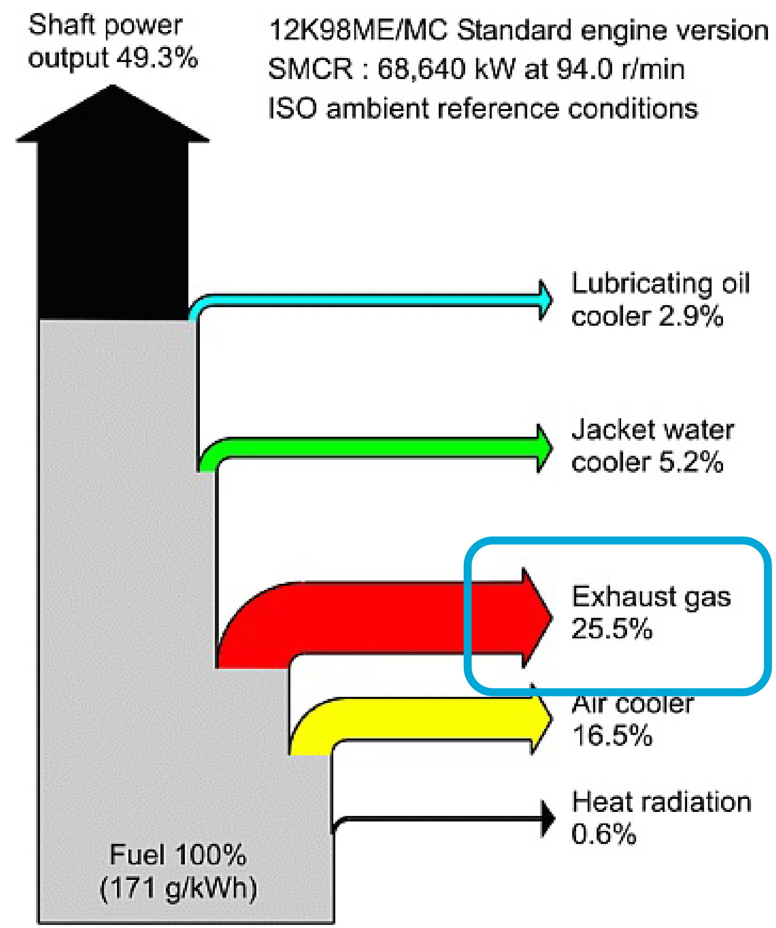
Introduction

- Greenhouse gas (CO_2) is a major contributor to global warming.

- Burning fossil fuels emit CO_2 in to the atmosphere.

- Ships emit about 1 billion tonnes of CO_2 annually.

- IMO has adopted energy-efficiency measures.
- They have set a series of baselines (EEDI) to be met by ships.
- By 2025, all new ships will be 30% more energy efficient than those built in 2014.
- Ships' energy consumption and CO_2 emissions could be reduced by **up to 75%** by applying operational measures and implementing existing technologies.
- Waste heat recovery systems (WHRS) is one of those technologies and a promising one.

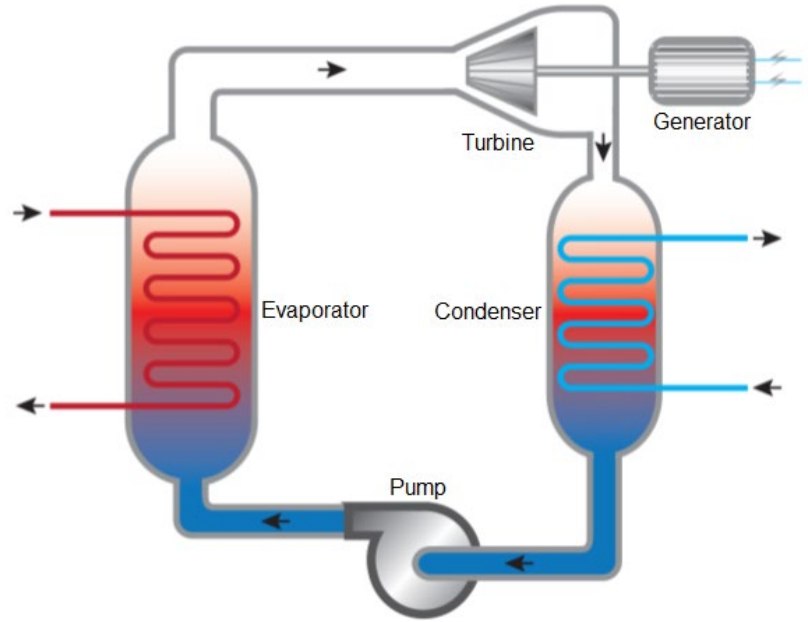


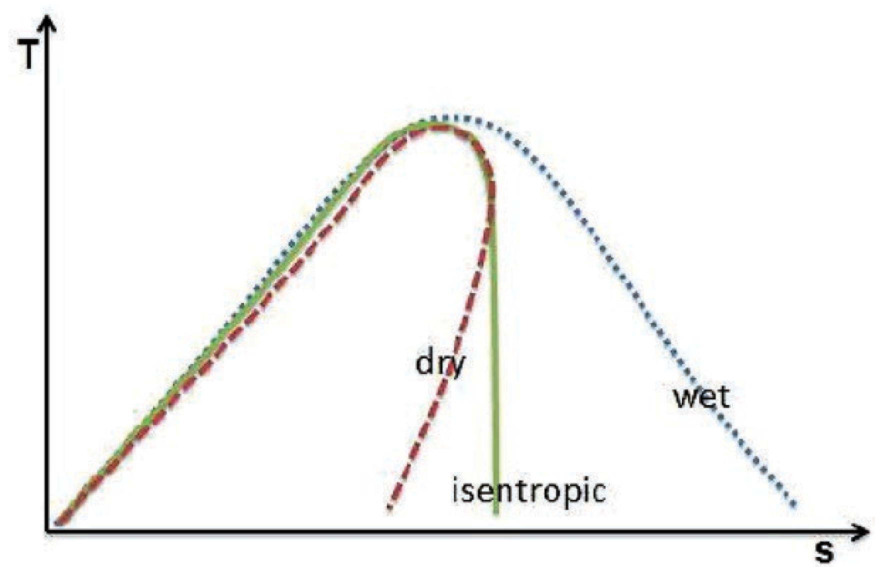
Review:

- Several WHRS technologies are available.
- Organic Rankine cycle (ORC) is one the most promising system.
- Plant simplicity, net efficiency and fluid choice flexibility.
- ORC has several advantages over water/steam system.

Challenges:

- Design and operation limitation factors.
- Off-design conditions.
- Engine dynamics.





Objective

Fluid screening:

- Screening methodology is devised to find a suitable fluid and plant layout.
- Influence of low temperature condenser cooling fluid on ORC plant and performance.

Modelling:

- Build a dynamic simple-ORC plant model by modification from an existing dynamic SRC model.
- Develop a dynamic recuperative-ORC plant model from the simple-ORC plant model.
- Build and implement a dynamic pump element into the ORC plant models.
- Comparison of dynamic ORC plant models to Cycle-Tempo ORC plant models.

Off-design performance analysis:

- Off-design performance analysis of ORC-WHRS plant models to off-load conditions.

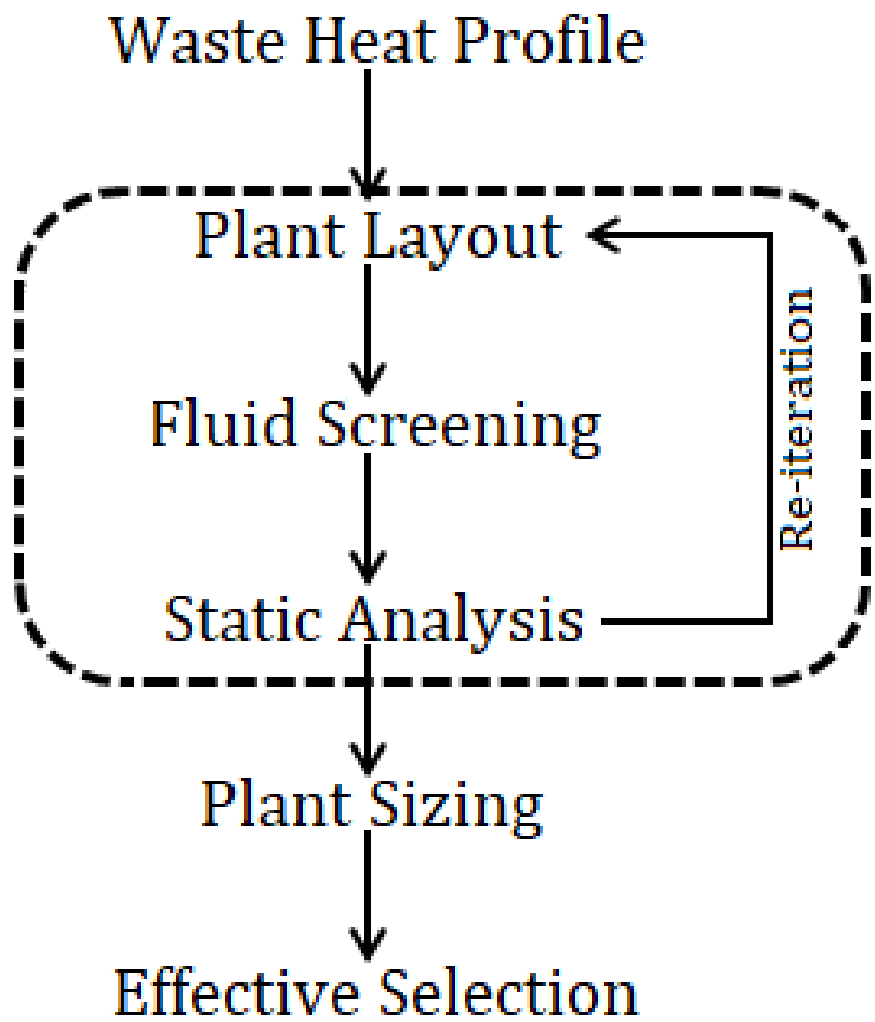
Dynamic and sensitivity analysis:

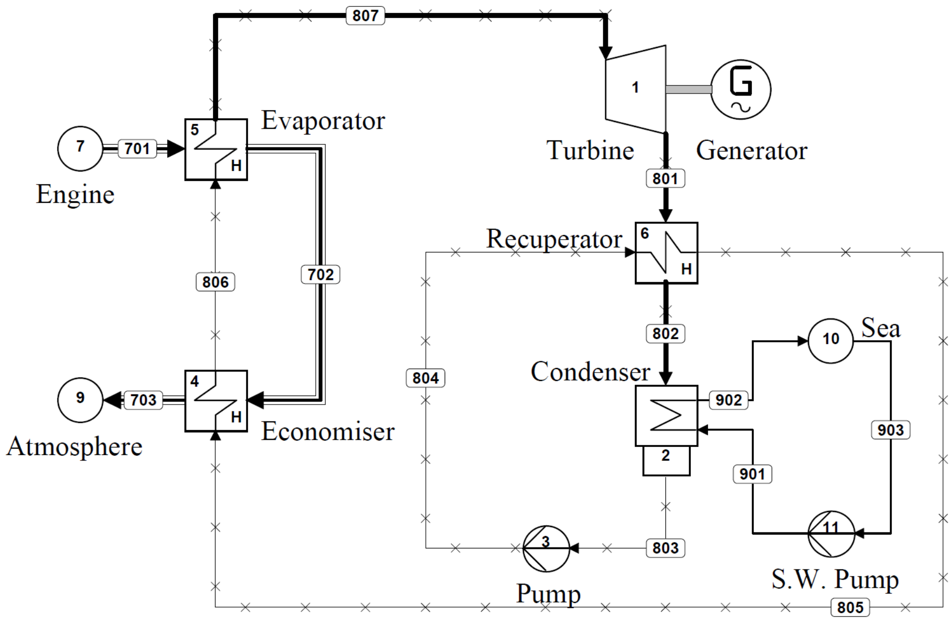
- Sensitivity analysis of ORC plant model.
- Analyse the dynamic behaviour of the ORC plant model.

Fluid Screening

Considerations:

- Sub-critical ORC plant.
- Exhaust gas data (product guide).
- Sea water as cooling fluid.
- Turbine inlet pressure of 30 bar.
- Power density as selection parameter.
- Isentropic and dry organic fluids.
- Simple & recuperative-ORC plants.



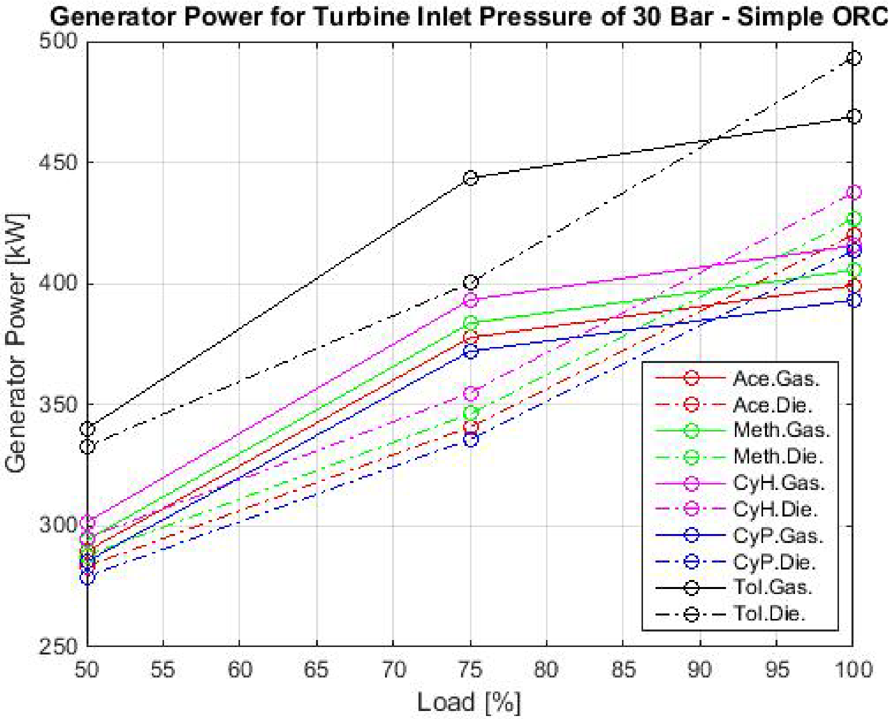


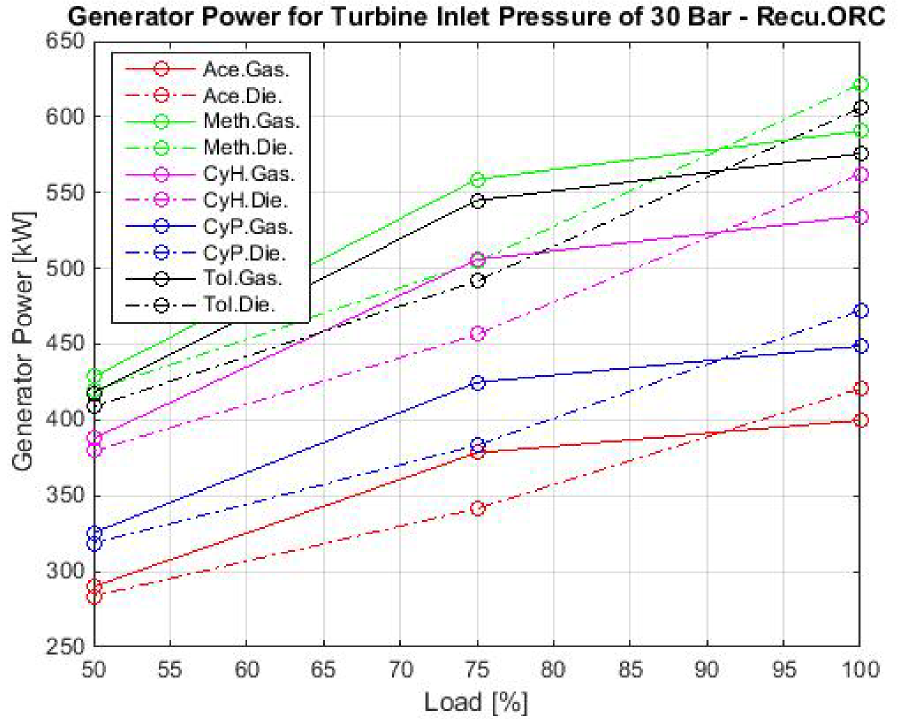
Functioning Fluids	
Acetone	R113
Butane	R114
1-Butene	R123
cis-2-Butene	R141B
Cyclohexane	R236ea
Cyclopentane	R245ca
Isobutane	R245fa
Ibutene	R365mfc
Ipentane	R436a
Methylcyclohexane	R436b
Neopentane	T2Butene
Pentane	Toluene
R11	

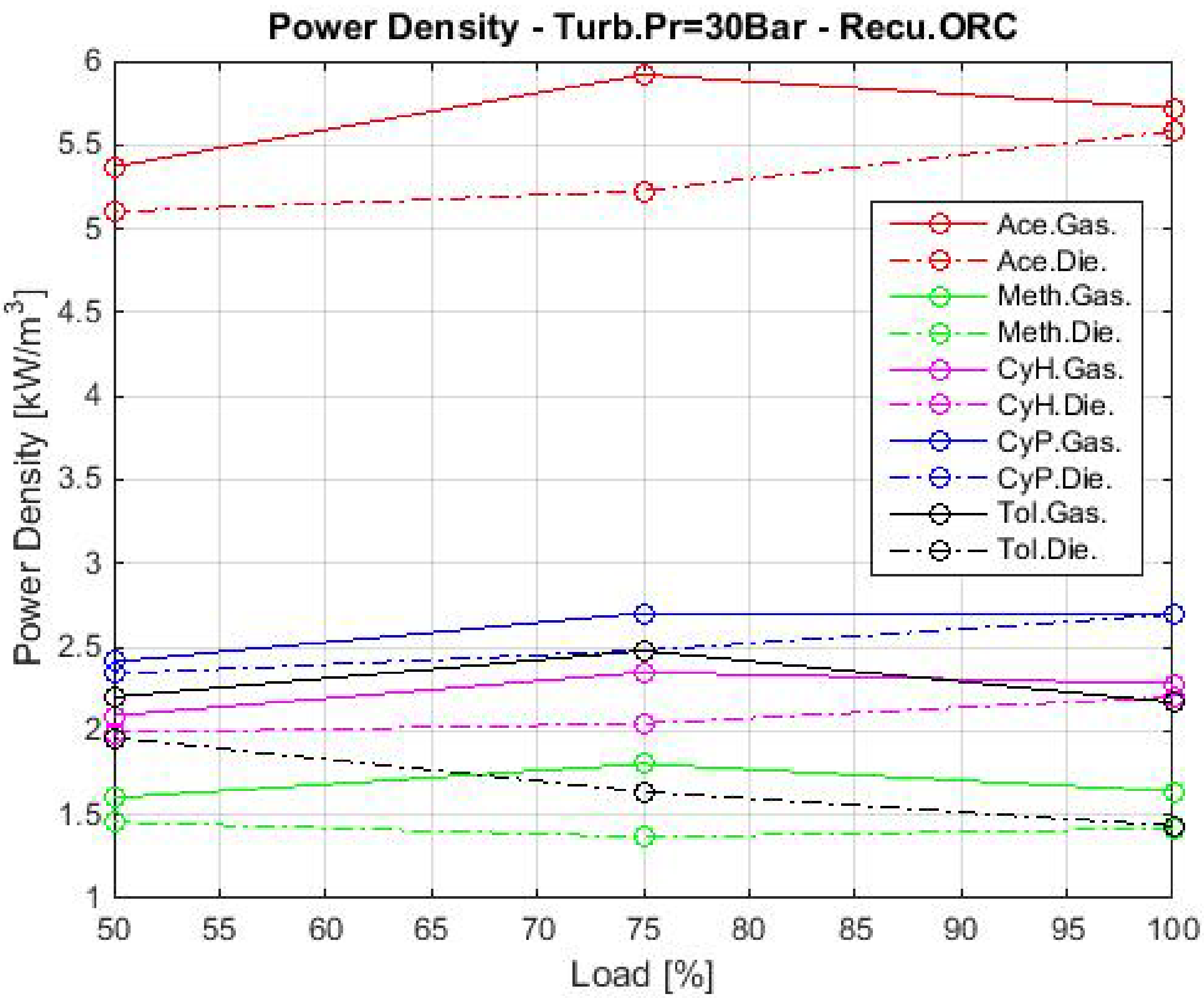
- Suitable for dry type fluids.
- Increases boiler inlet temperature.
- Increases thermal efficiency.

- Not all fluids may be suitable.
- Few are restricted for use by law.
- Ratio of kW per kg/s used initially.

- Suitable fluid were analysed in simple-ORC and recuperative-ORC plants.
- Analysis performed for three load points for engine in diesel and gas modes.

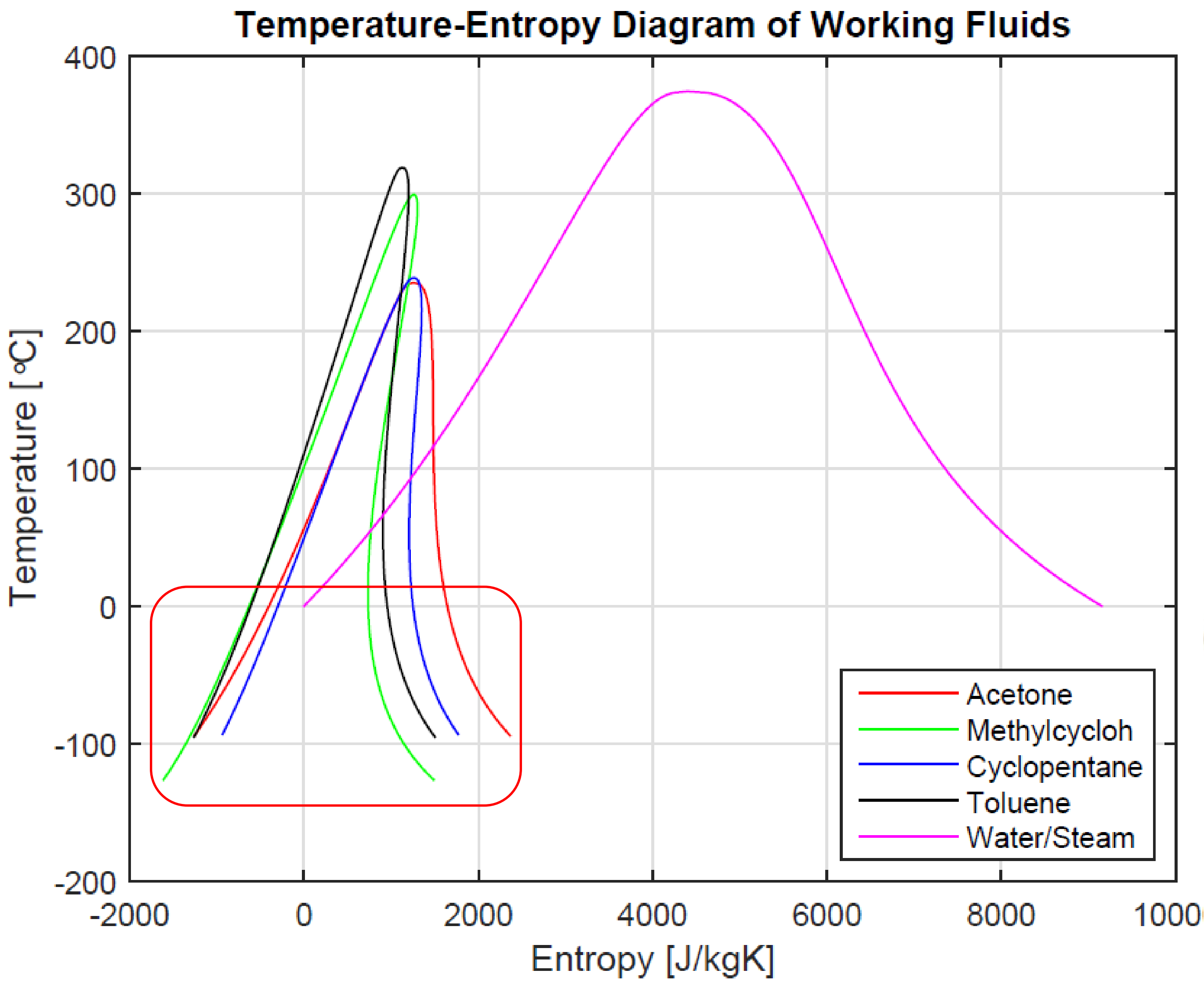


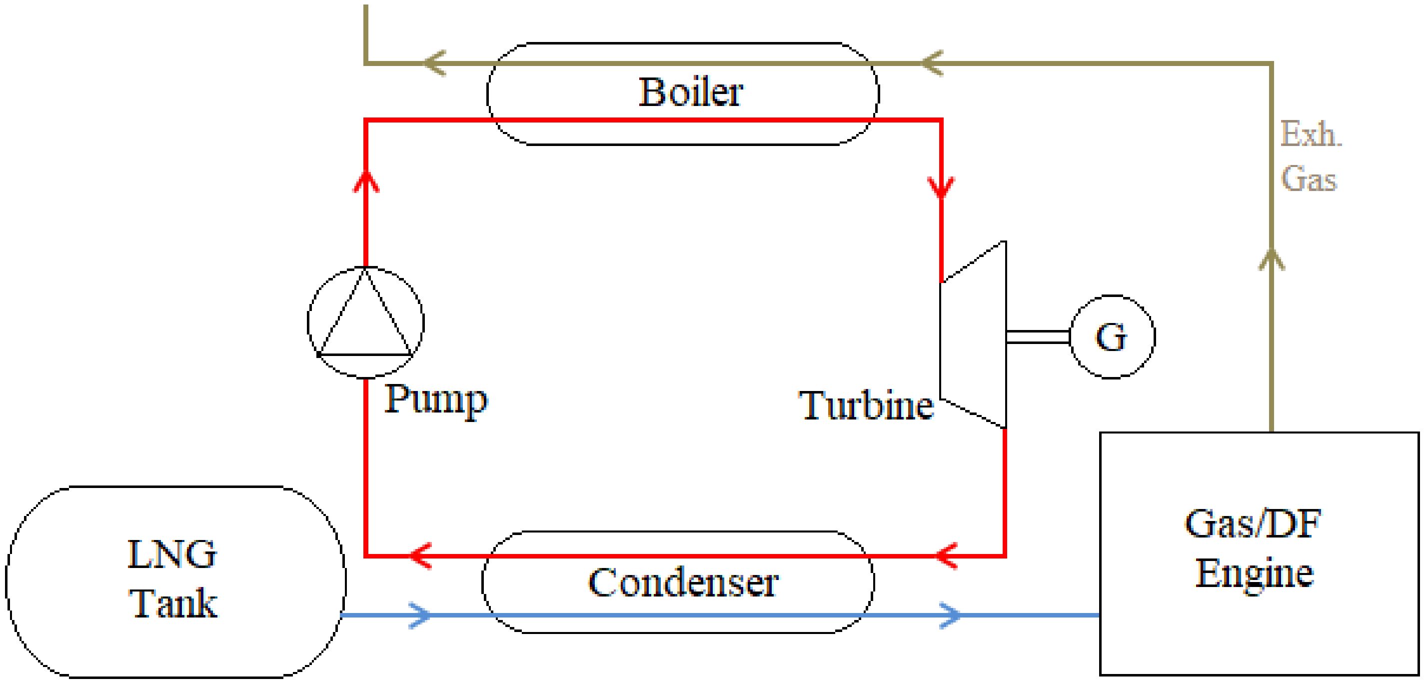




- Acetone based simple-ORC plant.
- Cyclopentane based recuperative -ORC plant.

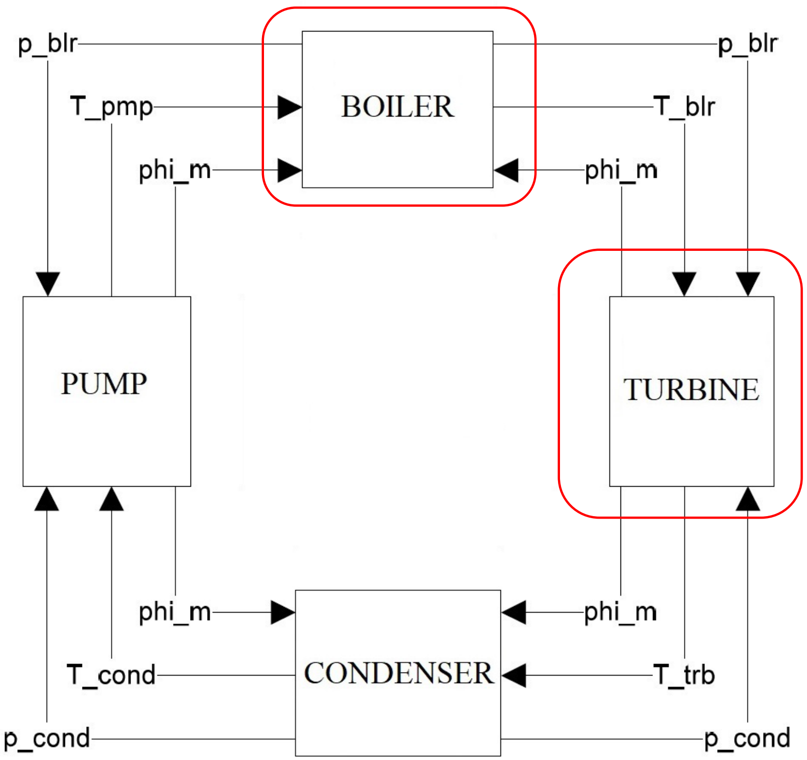
Influence of Cooling fluid Temperature

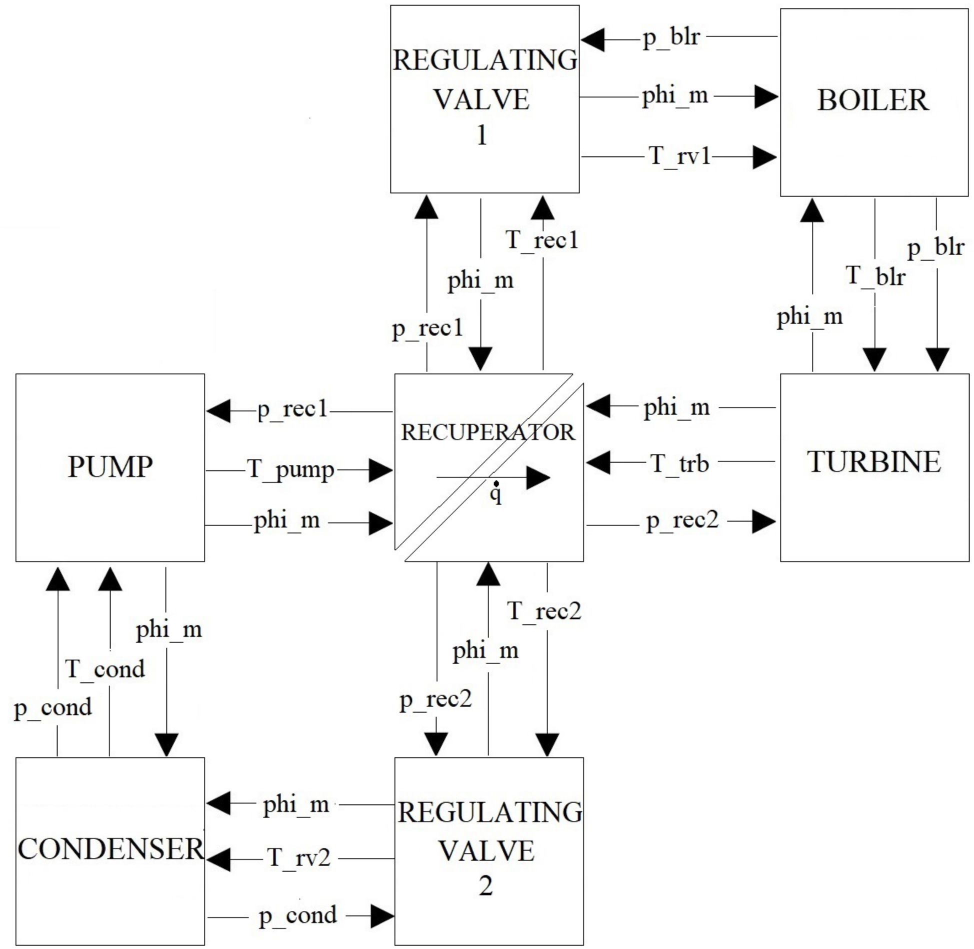




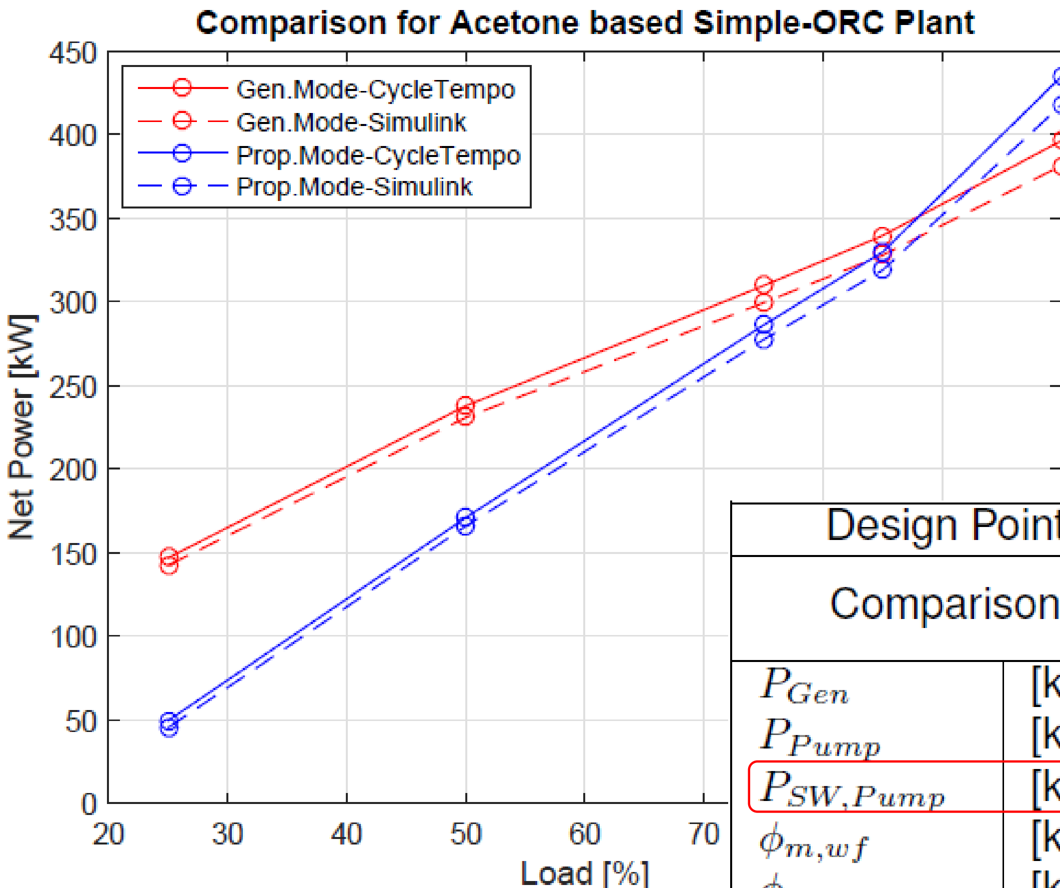
- Increase in net power/net energy efficiency by 39%.
- Decrease in plant volume by 25%.
- Increase in plant power density by 82%.

Dynamic Plant Modelling





- Volume element for heat exchangers.
- Resistance element for pumps and turbine.
- Modified from an existing SRC model.



Comparison

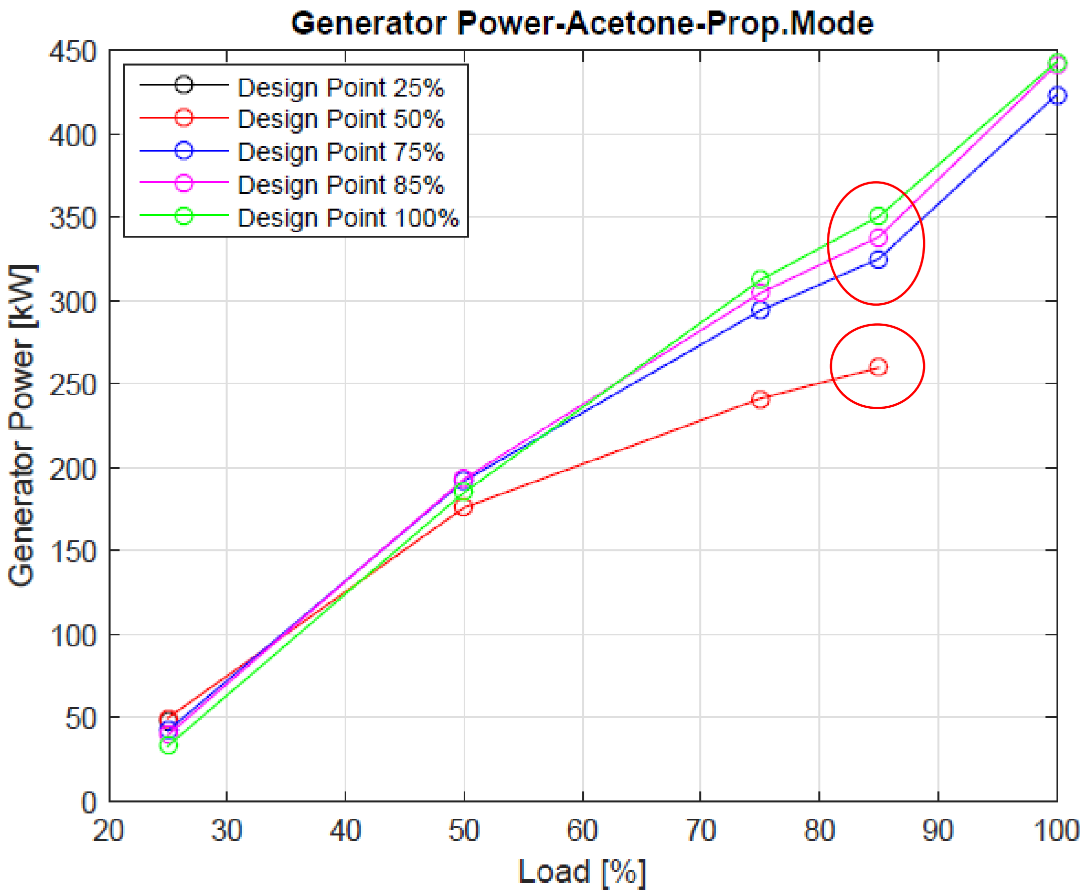
- Both models verified
- Design points from 25 to 100%.
- Diesel B model data.
- Acetone based Simple-ORC.

Design Point		100%		
Comparison		Cycle-Tempo	Model	Error [%]
P_{Gen}	[kW]	420.53	404.53	-3.80
P_{Pump}	[kW]	20.35	20.30	-0.25
$P_{SW,Pump}$	[kW]	3.84	2.77	-27.86
$\phi_{m,wf}$	[kg/s]	3.38	3.37	-0.32
$\phi_{m,sw}$	[kg/s]	43.16	43.02	-0.33
p_{evap}	[bar]	30.00	29.92	-0.26
p_{cond}	[bar]	0.57	0.57	0.00
$T_{eg-out,evap}$	[°C]	325.43	325.68	0.08
$T_{eg-out,econ}$	[°C]	165.00	165.82	0.50

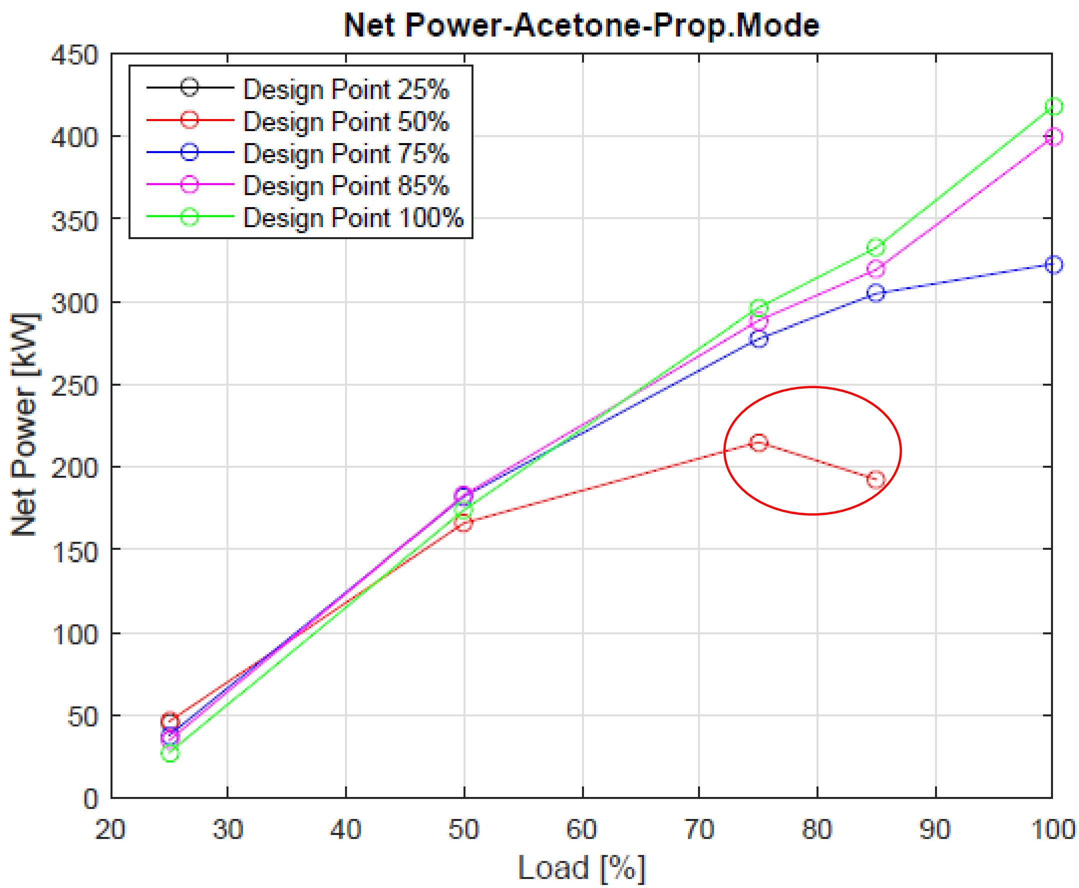
- Engine load points of 25, 50, 75, 85 and 100 are considered.
- These load point data for both generator load and propeller load are considered of SWD Engine.

	Acetone-Simple ORC	Cyclopentane - Recuperative ORC
Generator Load	×	×
Propeller Load	×	×

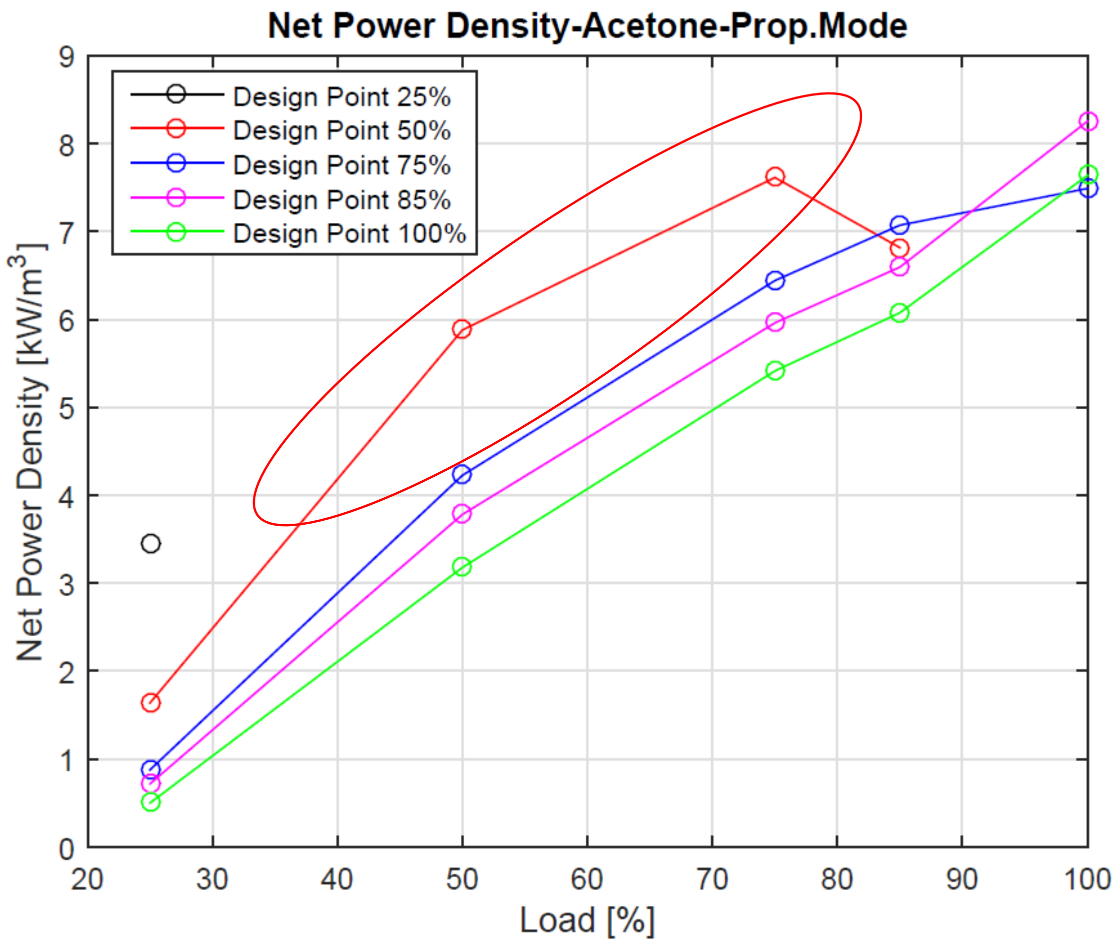
- Engine load from 25 to 100%
- Turbine design pressure is 30 bar.
- Plants of higher design points generate more power for a wider engine load.
- Overshoot into critical point for plant designed at low loads.
- By-pass line may be required.



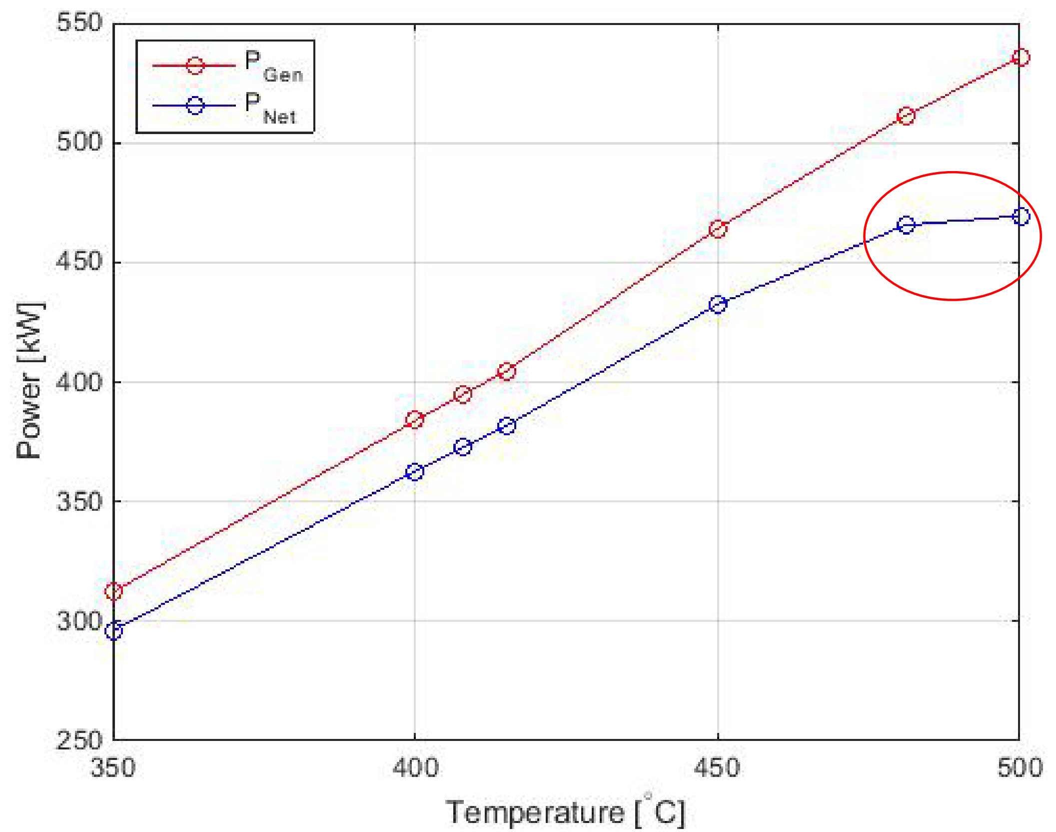
- By-pass line may be use way sooner.
- Pump power is significant for plants of higher design points on high off-loads.
- Sea water cooling fluid mass flow rate limit.



- Plants of lower design points have better power density for a wider engine load.
- Off-design analysis should be extended with SFC and operational profile.

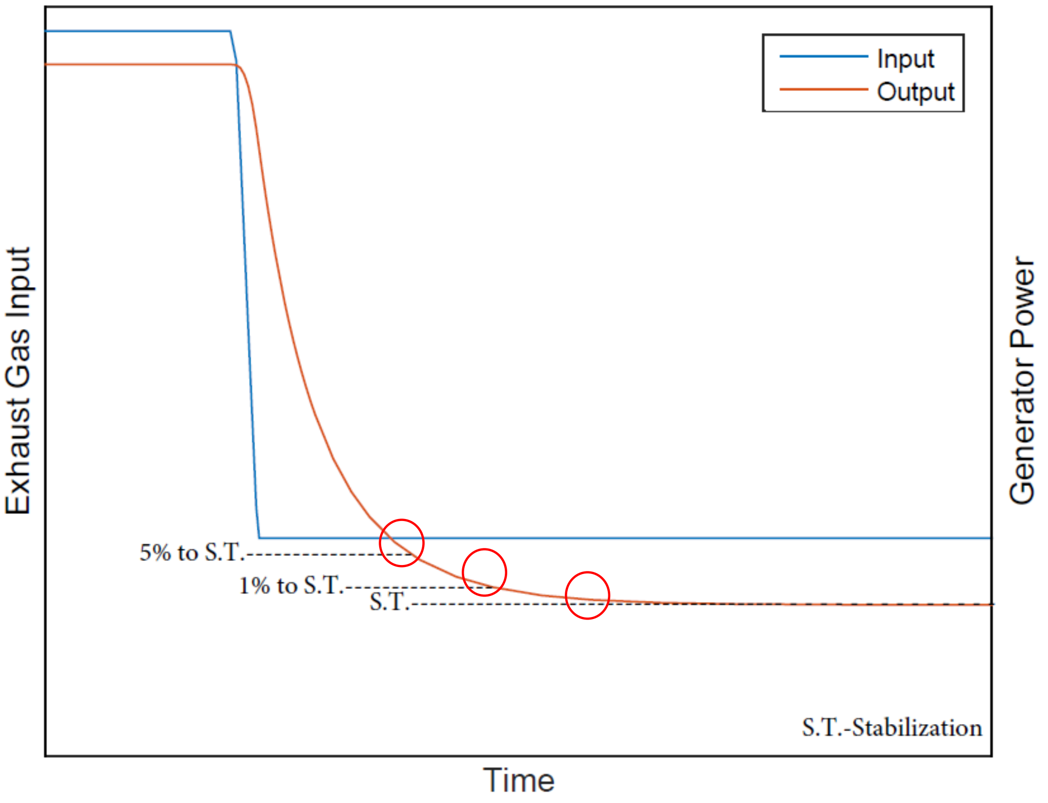


- This analysis is to understand uncertainties.
- Acetone based simple-ORC plant model used.
- Analysed for varying exhaust pressure, temperature and mass flow.

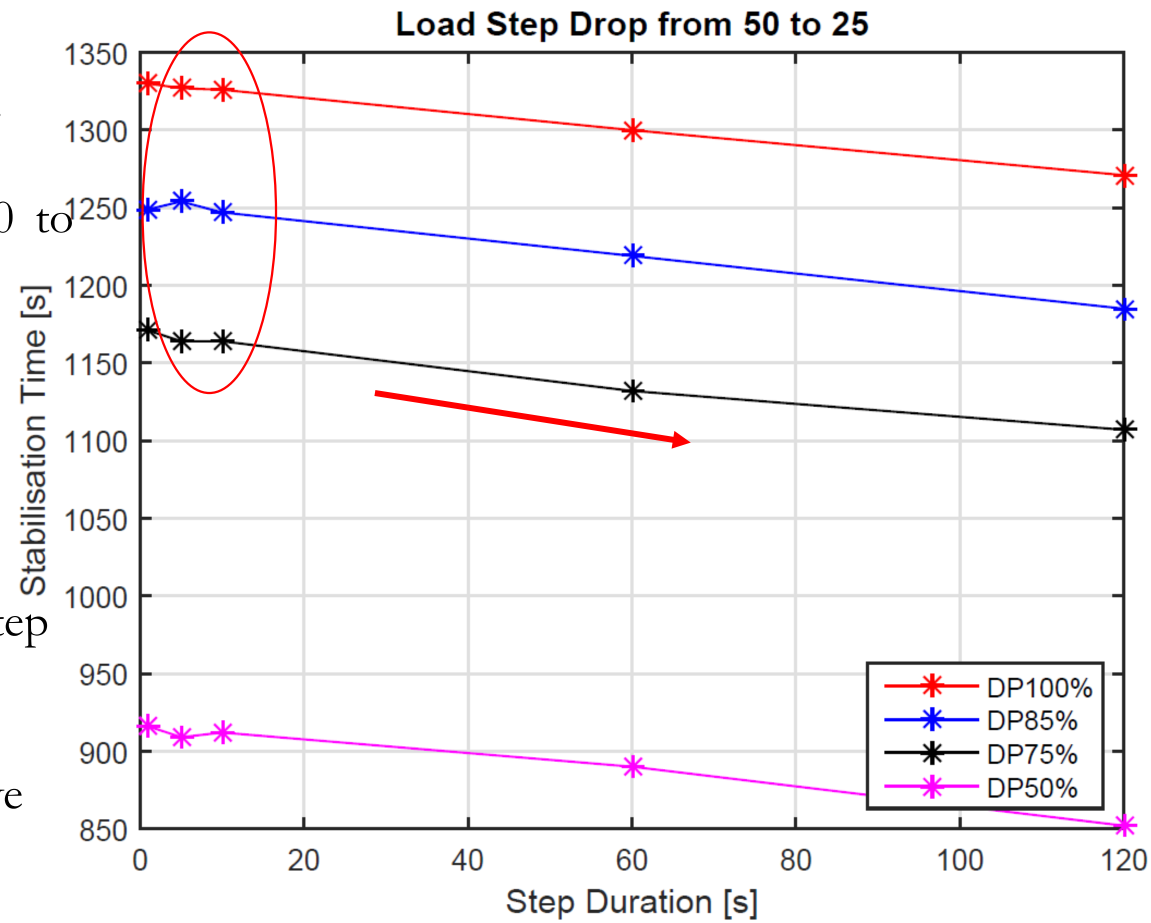


- Sea water cooling fluid mass flow rate limit.
- High pump power required.

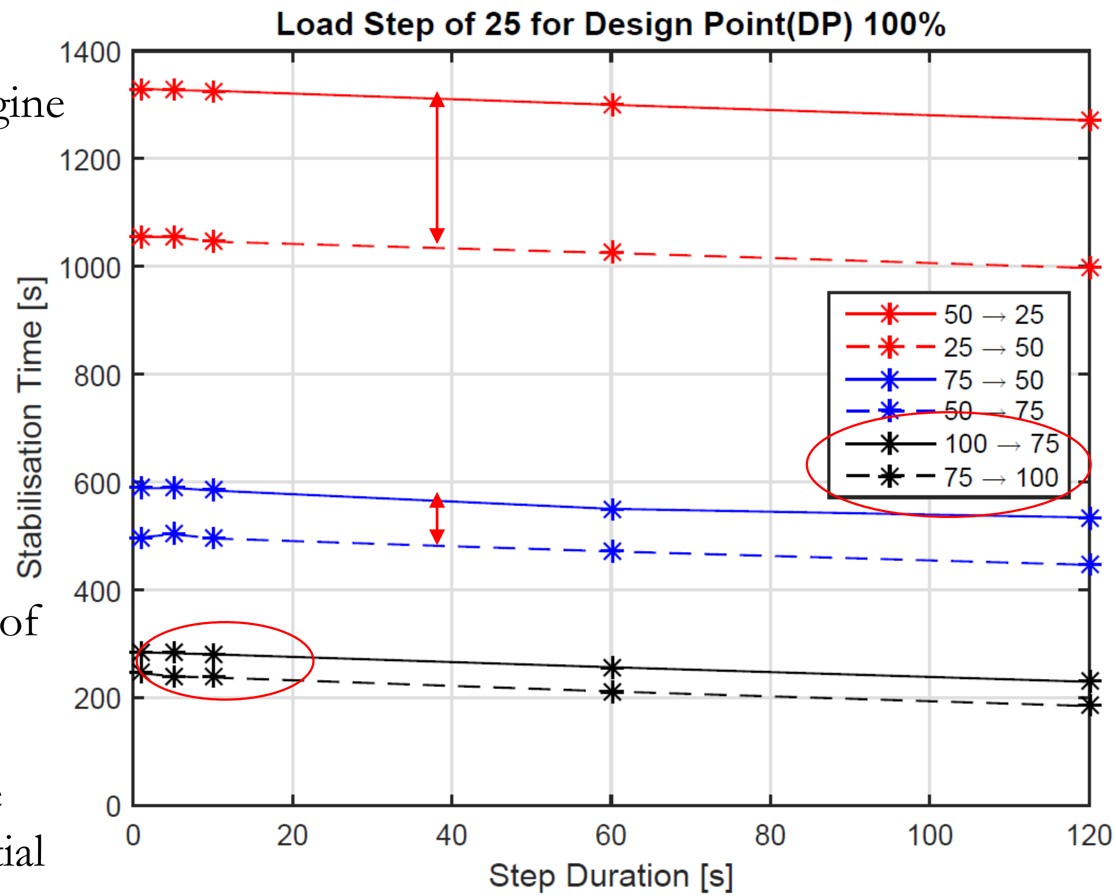
- Engine load points of 25, 50, 75, 85 and 100% are considered.
- Acetone based simple-ORC is used.
- Load-drop/rise step function.
- Load between 25% – 100%.
- Step duration 0 – 120 sec.
- 5, 1 and 0.1% to stabilisation.



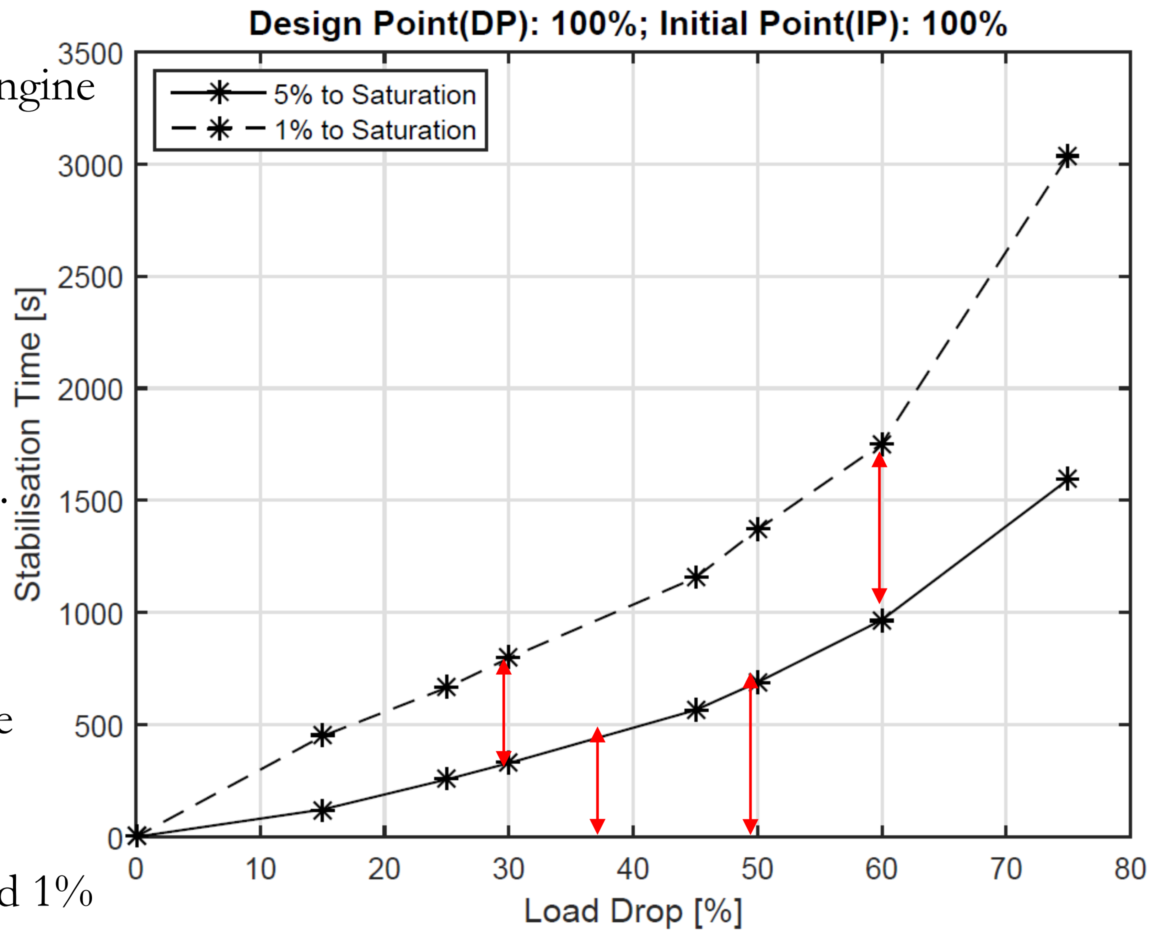
- Plants for different design points.
- Same engine load drop from 50 to 25%.
- Step duration 0 – 120 sec.
- 5 to stabilisation used.
- Stabilisation is faster for longer step durations.
- Plants of lower design points have relatively faster response to same engine load variation.



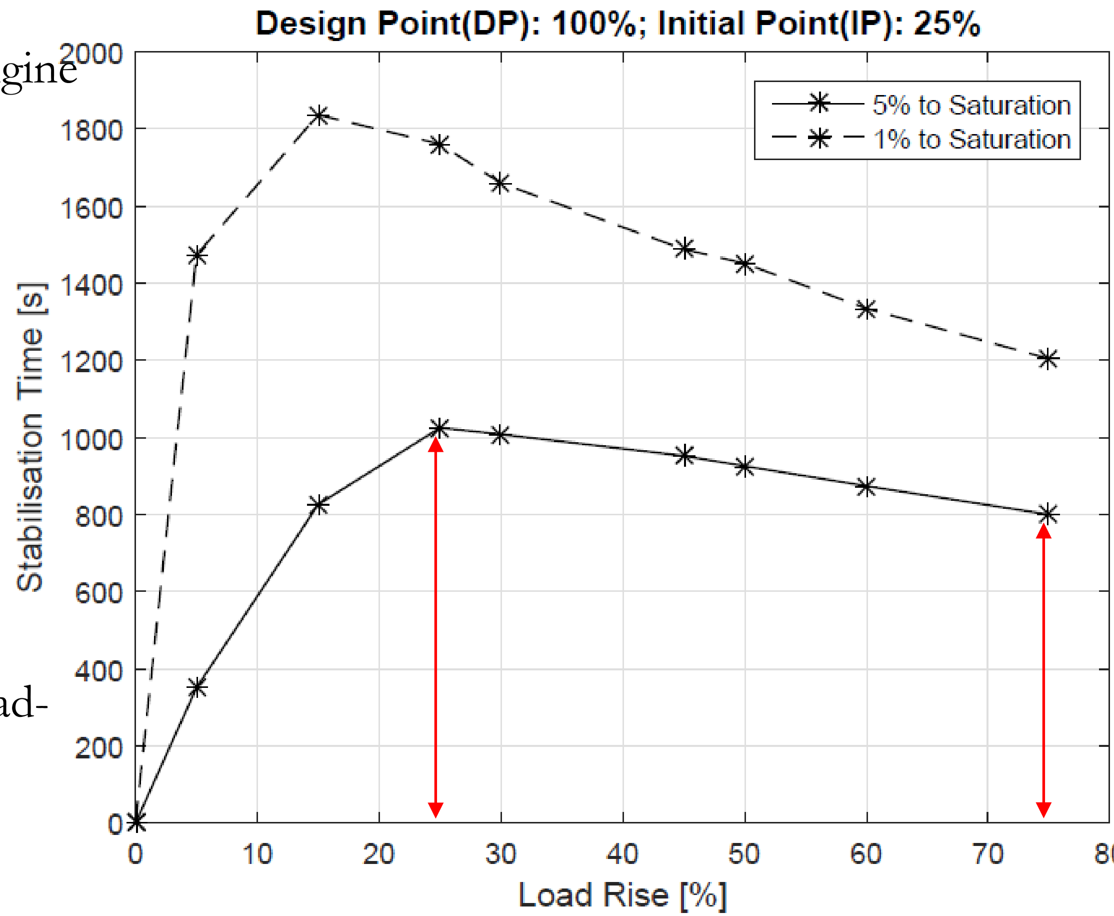
- Plant designed for 100% engine point.
- Engine load step of 25%.
- Step duration 0 – 120 sec.
- 5 to stabilisation used.
- Load rise is faster than load drop of same step.
- Time difference between load rise and load drop increases as the initial load decreases.



- Plant designed for 100% engine point.
- Load-drop step function.
- Step duration 60 sec.
- 5% and 1% to stabilisation used.
- Initial load of 100%.
- Stabilisation time is longer as the load drop is larger.
- Time difference between 5% and 1% increases as the load drop is larger.



- Plant designed for 100% engine point.
- Load-rise step function.
- Step duration 60 sec.
- 5% and 1% to stabilisation used.
- Initial load of 25%.
- Stabilisation time is longer for load-rise to 50% than to 100%.



Conclusions:

- Acetone may be the most suitable fluid for marine application based on PD.
- Acetone - net fuel saving of about 3.0%.
- Using LNG – increased net fuel saving from 3.0 to 4.1% and PD from 7.4 to 13.3 kW/m3.
- Methylcyclohexane - net fuel saving of about 4.3%.
- Plants of lower design points have better power density for a wider engine load.
- Cooling water mass flow rate and the pump power are the limiting parameters.

Recommendations:

- Include other selection parameters.
- Investigate the application of LNG.
- Validate the ORC plant models with real plant data.
- Include operational profile of the vessel.
- Investigate capex and opex.
- Investigate into energy storage device.

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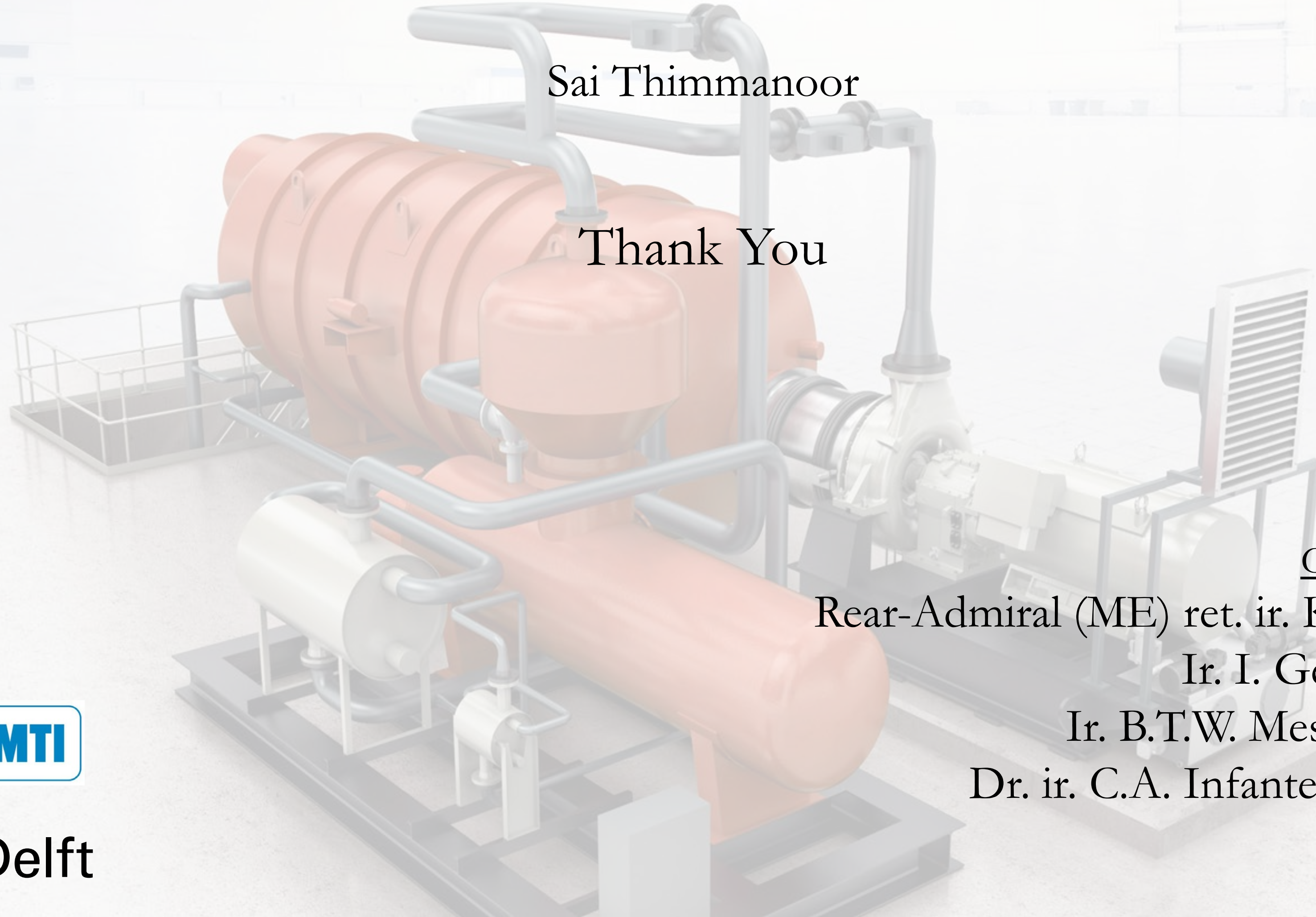

Thank You

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