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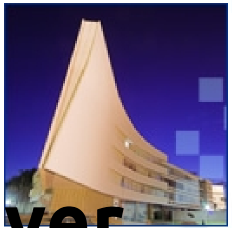
February 2015



Analysis and Optimisation of a Receiver Tube for Direct Steam Generation in a Solar Parabolic Trough Collector

Henriette Nolte[1], T. Bello-Ochende[2] and J.P. Meyer[1]

[1]Department of Mechanical and Aeronautical Engineering
University of Pretoria, Pretoria, South Africa, 0002

[2]Department of Mechanical Engineering
University of Cape Town, Rondebosch, South Africa, 7701

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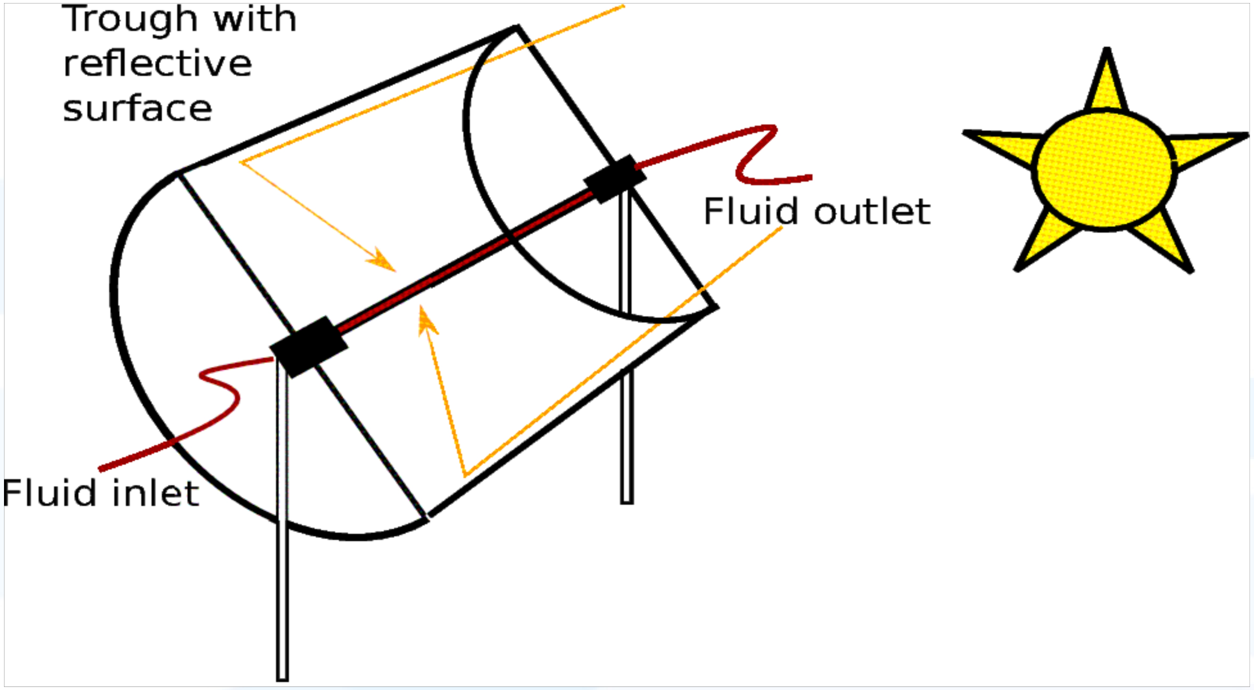
Parabolic Trough



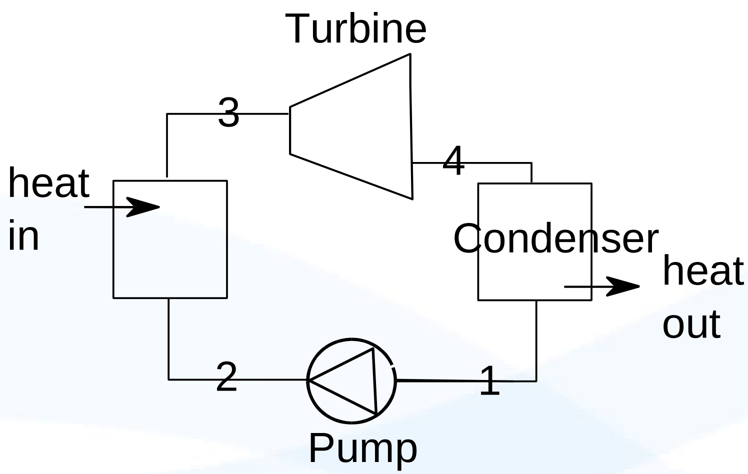
Advantages

- One Axis Tracking
- Moderate Temperatures (200 – 400 °C)
- Water can be used as working fluid
- Tried and tested technology

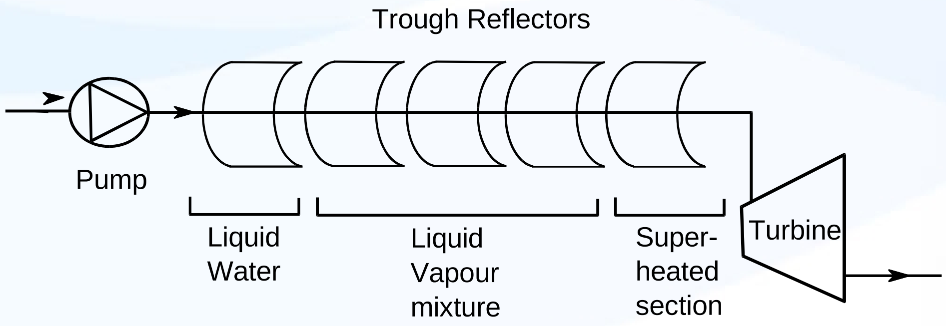
Disadvantages

- Water not as thermally stable as thermal oil
- Lower temperatures means smaller temperature differential (Disadvantage/Advantage)

Background and Scope



Simple Rankine Cycle



Focus: Receiver tube

Small scale:

50-350kW turbine work

Receiver Thermal Analysis

1D Heat Transfer through receiver:

- Convection on inner tube perimeter

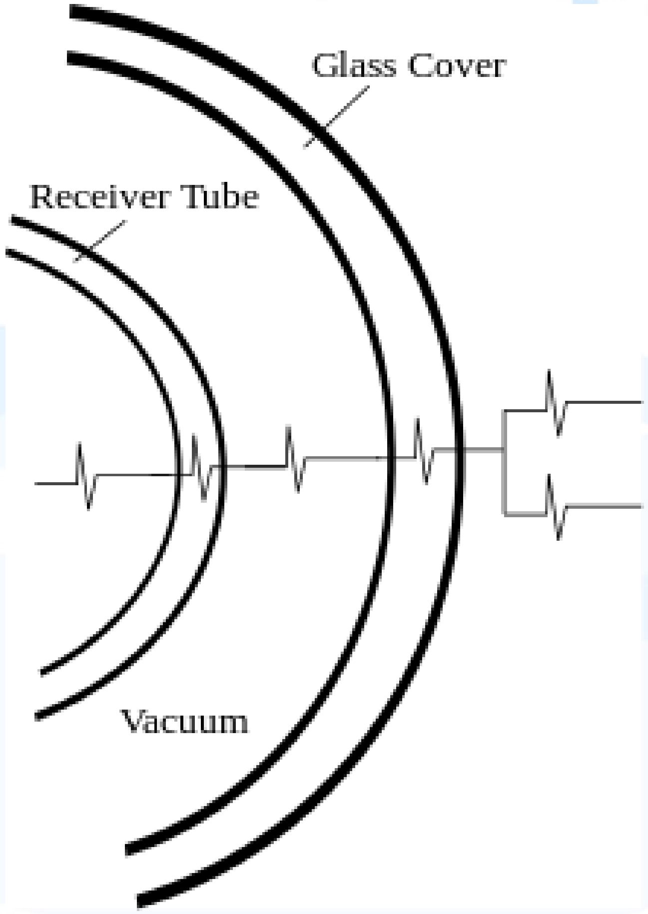
- Conduction through receiver tube wall

- Radiation from receiver tube
  to inner glass cover
  (if vacuum is maintained)

- Conduction through the glass cover

- Radiation losses from the cover

- Convection losses due to wind or natural convection
- Forced convection investigated with wind velocity of
  2 m/s



Heat Transfer and pressure drop correlations

Single phase regions:

Use of Gnielinsky for inner tube heat transfer coefficient
Friction factor: Petukhov for smooth tubes

Two-phase region:

Method described by Wojtan et al.[1] for heat transfer coefficient
Two-phase pressure drop obtained by Friedel correlation

Forced convection on outer glass cover:

Churchill and Bernstein

[1]Wojtan, L. Ursenbacher, T. Thome J.R. "Investigation of flow boiling in horizontal tubes: Part I- A new diabetic two-phase flow pattern map & Part II – Develpment of a new heat transfer model for stratified-wavy, dryout and mist flow regimes." *International Journal of Heat and Mass Transfer*. Vol 48. pp 2955-2985

First law analysis

Single phase regions

- Single phase regions (liquid and superheated region) , fluid temperature increase

- Regions divided into unit sections

- Each unit section solved iteratively in Python

- Glass cover temperature determined by energy balance and SciPy fmin

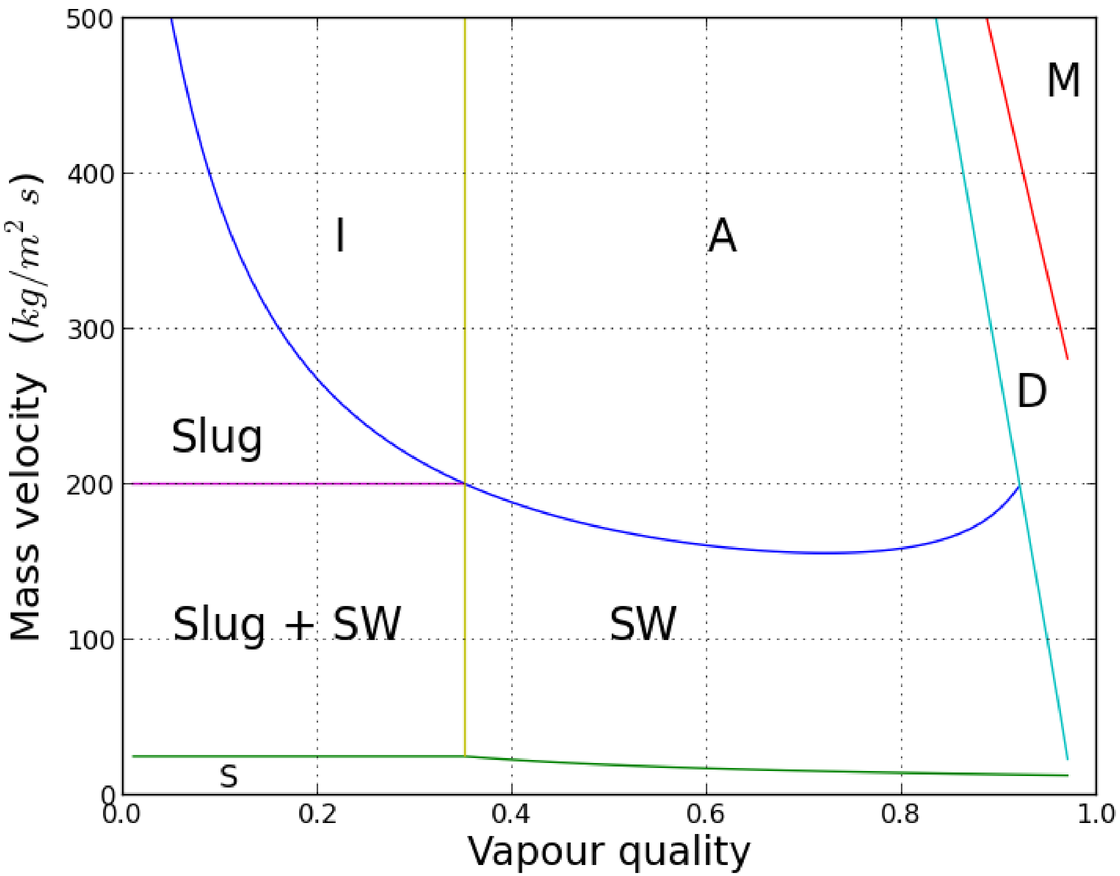
$$Q_{\text{rad, rec-cover}} = Q_{\text{conv, cover-amb}} + Q_{\text{rad, cover -sky}}$$

- Fluid properties temperature dependent

- Fluid properties obtained with CoolProp[2]

[2]Bell, I. "CoolProp," Feb 2013 [online]. Available: http://coolprop-sourceforge.net

First law analysis: Two-phase region



- Sections solved for each 2% quality change
- Flow regime determines heat transfer coefficient
- Heat transfer coefficient large for two-phase flow
- Receiver temperature stays reasonably constant for most part of the region
- Temperature spikes perceived when dryout occurs

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Pressure Drop

Single phase regions (Darcy Weisbach):

$$\Delta P_{fric} = f\left(\frac{L}{D_i}\right)\left(\frac{\rho}{2}\right)V^2$$

Two phase regions (Friedel):

$$\Delta P_L = 4f_L\left(\frac{L}{D_i}\right)\left(\frac{1}{2\rho_L}\right)G^2$$

$$\Delta P_{two-phase} = \Delta P_L \Phi^2$$

Limitation:

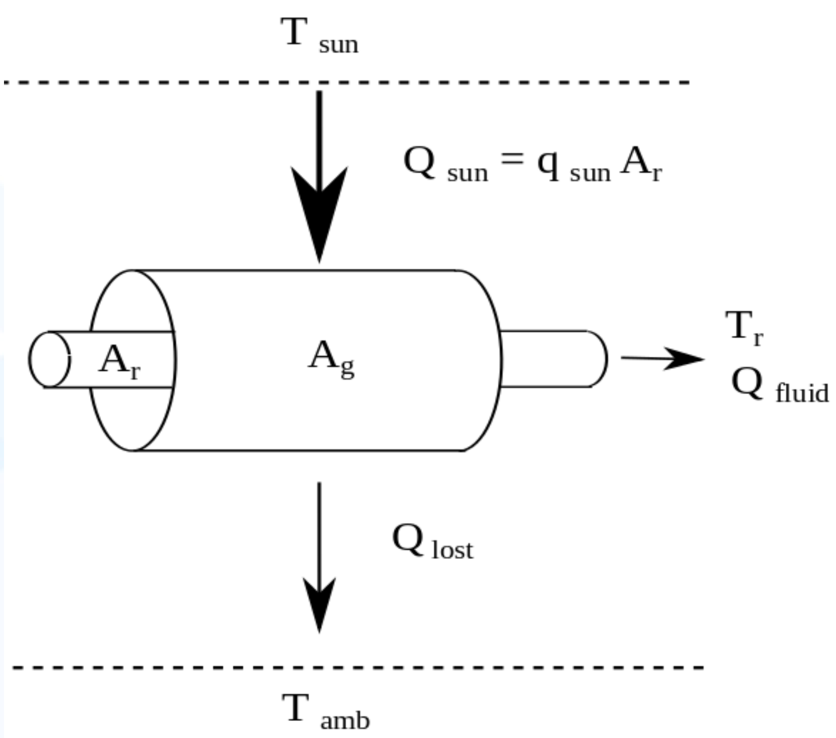
Momentum and Static losses not taken into account
To avoid added uncertainty of layout and fittings

Second Law Analysis

Entropy Generation due to[3]:

1) Finite temperature differences

$$S_{gen,dT} = \frac{E_{des}}{T_{amb}}$$



Exergy Destruction

$E_{in} = Q_{sun}(1 - T_{amb}/T_{sun})$

$E_{out} = Q_{fluid}(1 - T_{amb}/T_r)$

$E_{des} = E_{in} - E_{out}$

$S_{gen} = E_{des}/T_{amb}$

[3]Bejan, A. Entropy generation minimisation of finite size systems and finite time. CRC press; 1995.

Second Law Analysis

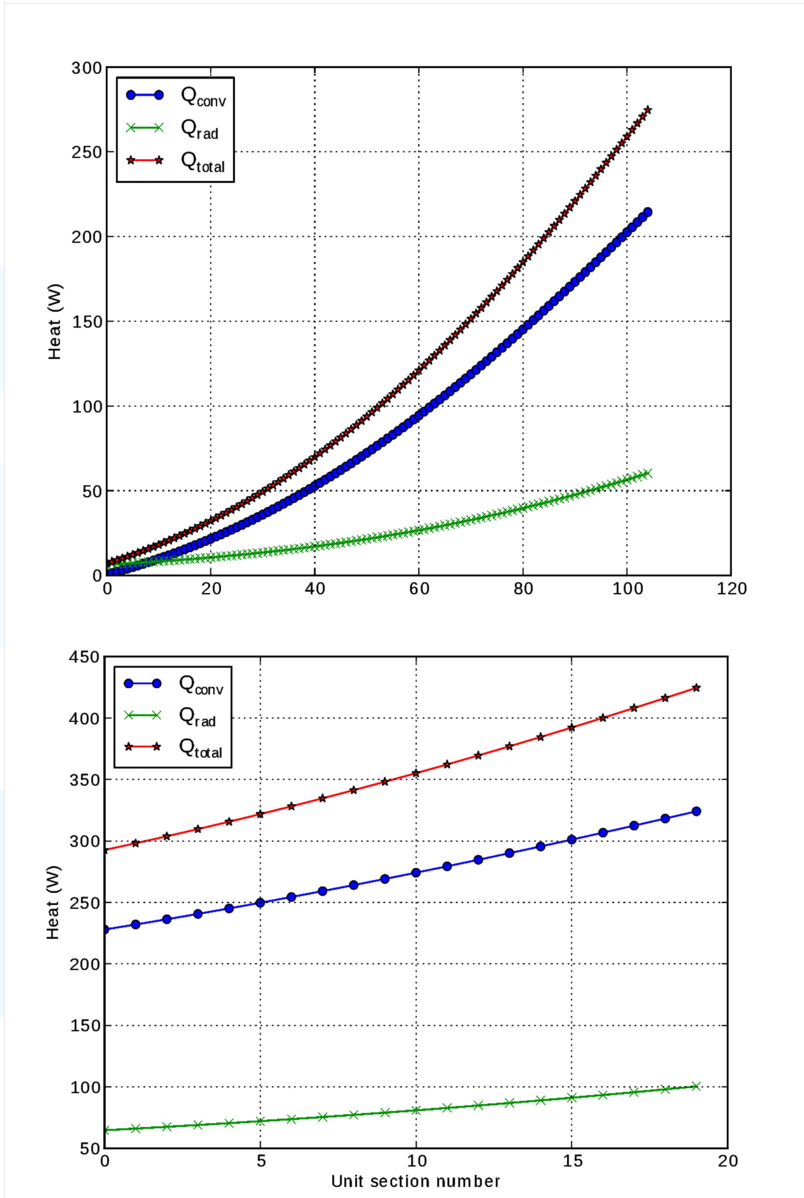
2) Entropy Generation due to fluid friction:

$$S_{gen,dP} = \frac{\dot{m}\,\Delta P}{\rho T}$$

Initial Parameters

T_{amb}	$20^{o}C$
Q_{sun}	2000 W
Turbine inlet	20% higher than T_{sat}
T_{sky}	$12^{o}C$

Validation: Single Phase Region



Heat losses throughout the liquid region and superheated region

- Base case parameters:
T_{sat} = 250 °C (4 MPa), m = 0.2 kg/s, D_i = 25 mm

- Initially radiation losses higher than convection

- Convection losses small initially

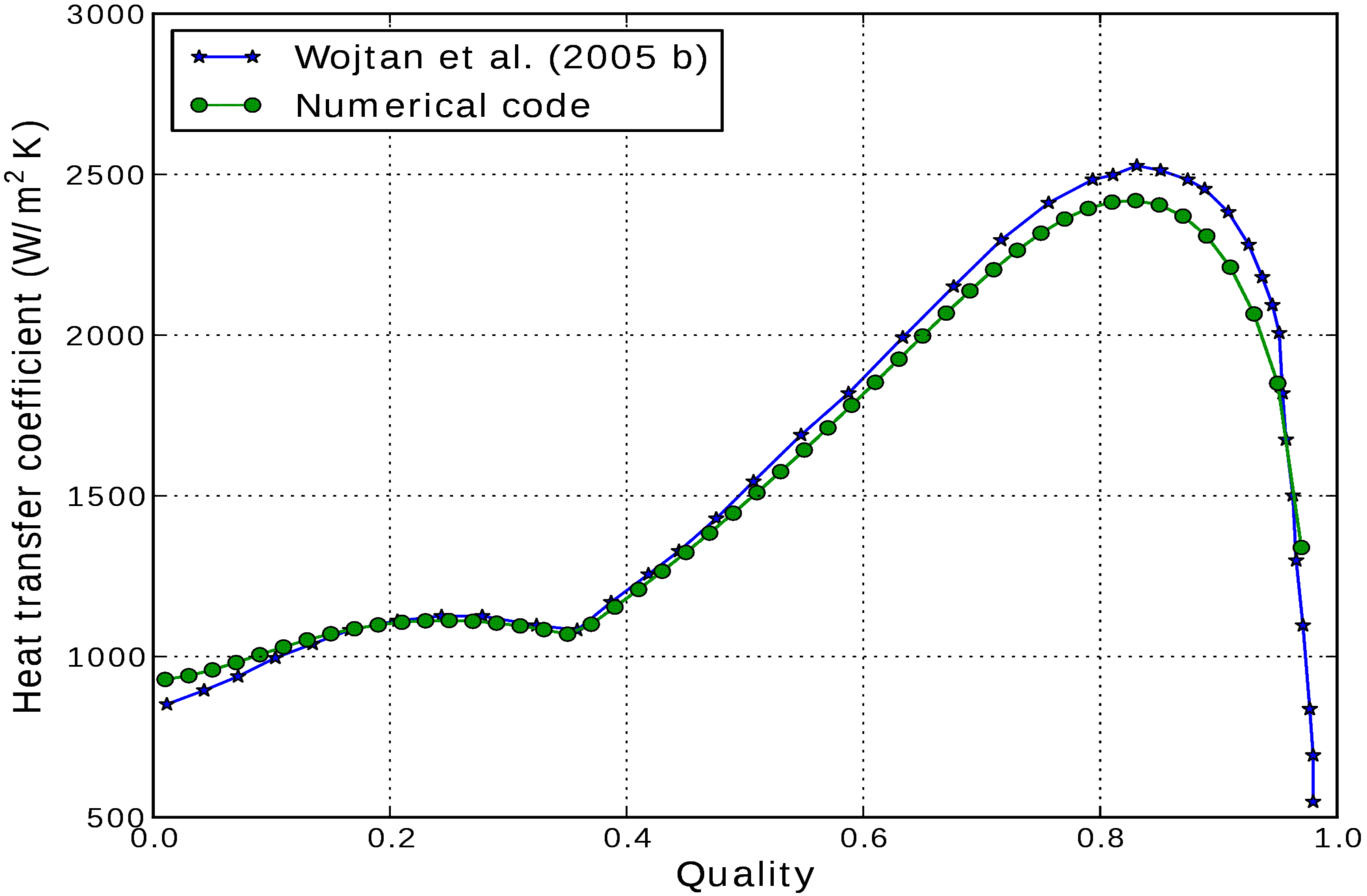
- Glass cover initially close to ambient for first 5 - 10 unit sections

- Liquid region much longer than superheated region

- Losses highly depended on cover temperature

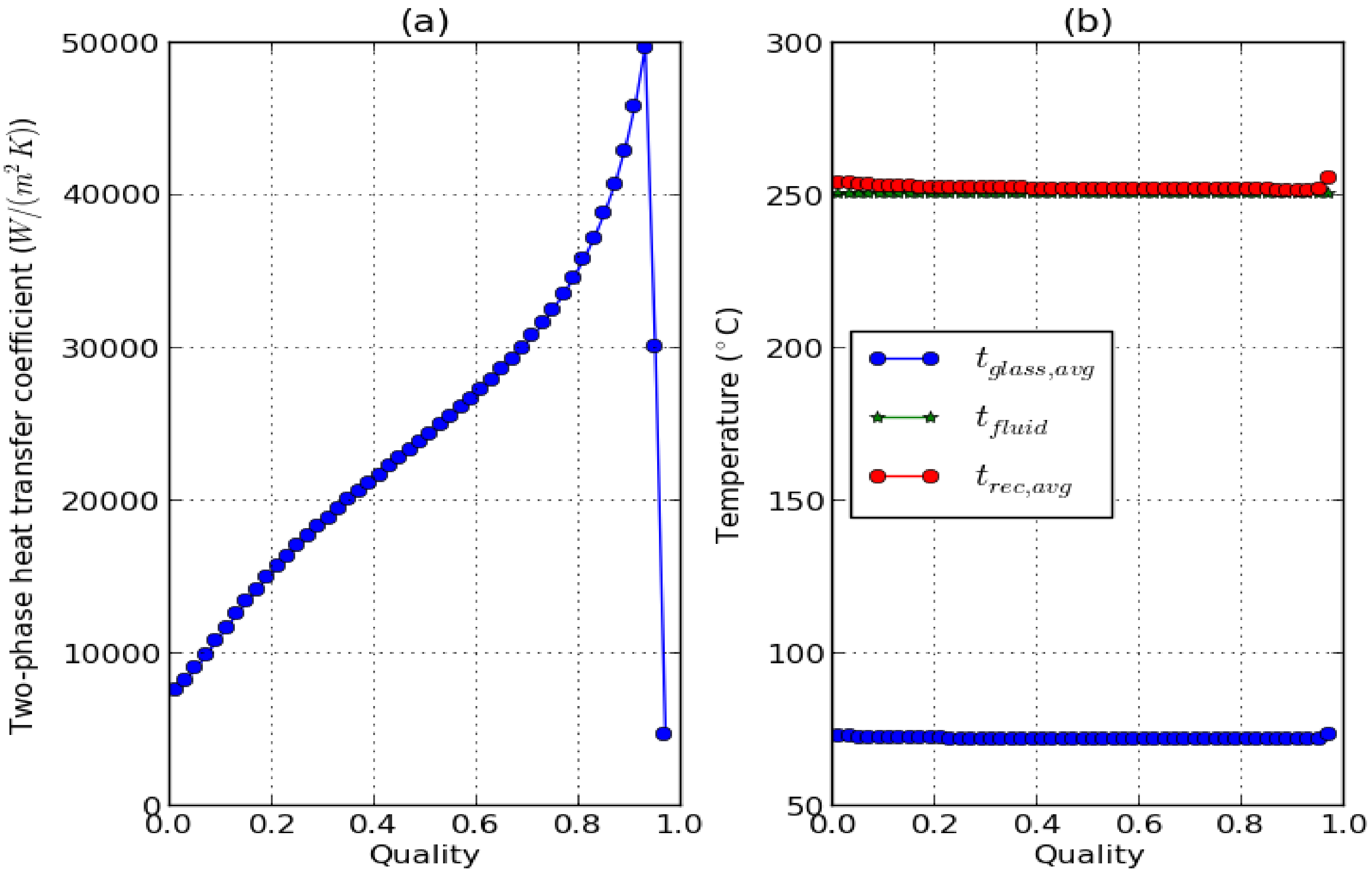
Validation: Two-phase region

Heat transfer coefficient comparison for R22 with following parameters:
T_{sat} = 5 °C , G = 150 kg/m²s (mass velocity),
D_i = 13.84 mm , q = 3.6kW/m²

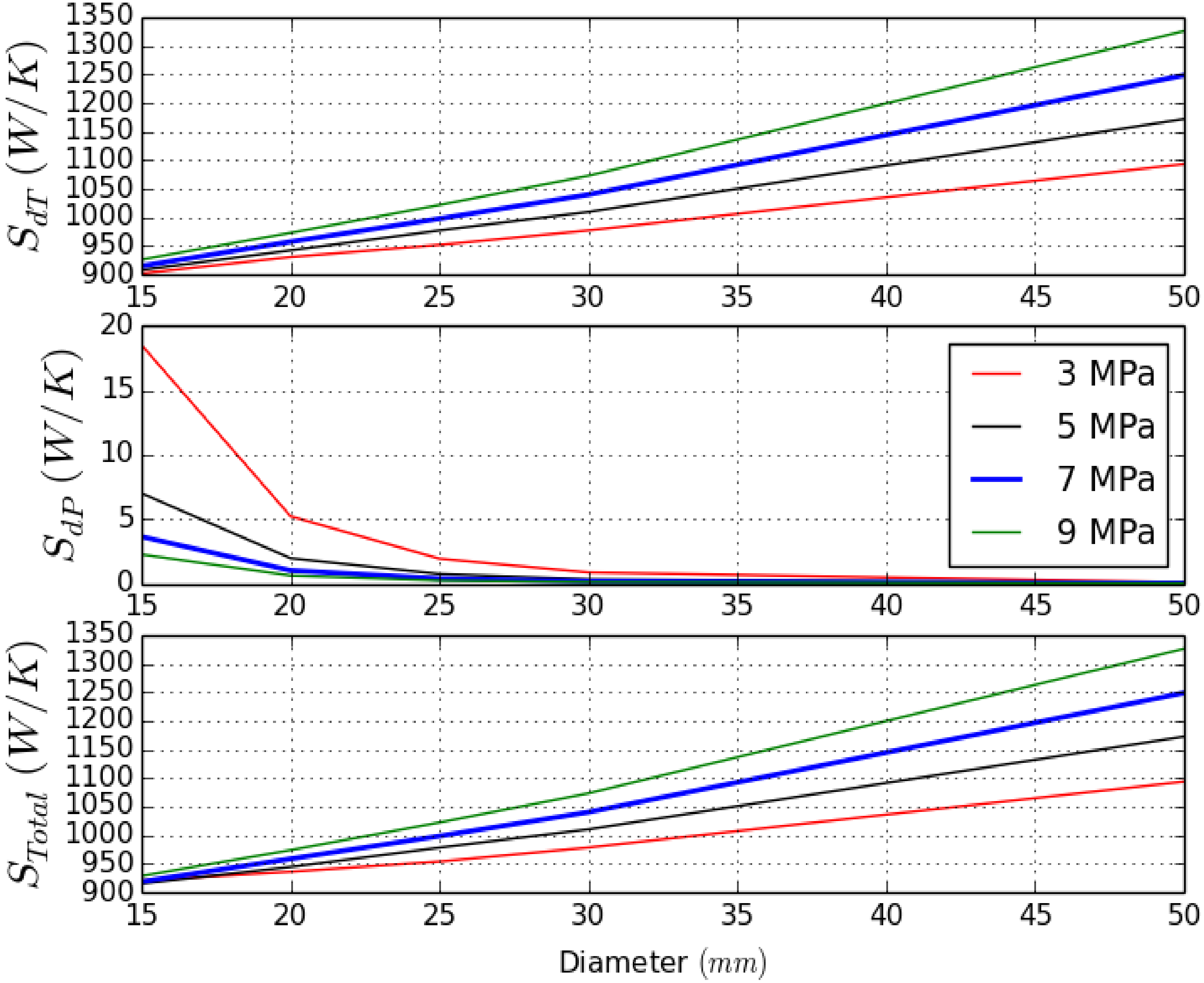


Validation: Two-phase region

Heat transfer coefficient comparison for base case parameters:
T_{sat} = 250 °C , m = 0.2 kg/s , D_i = 25 mm , Q = 2 kW/m

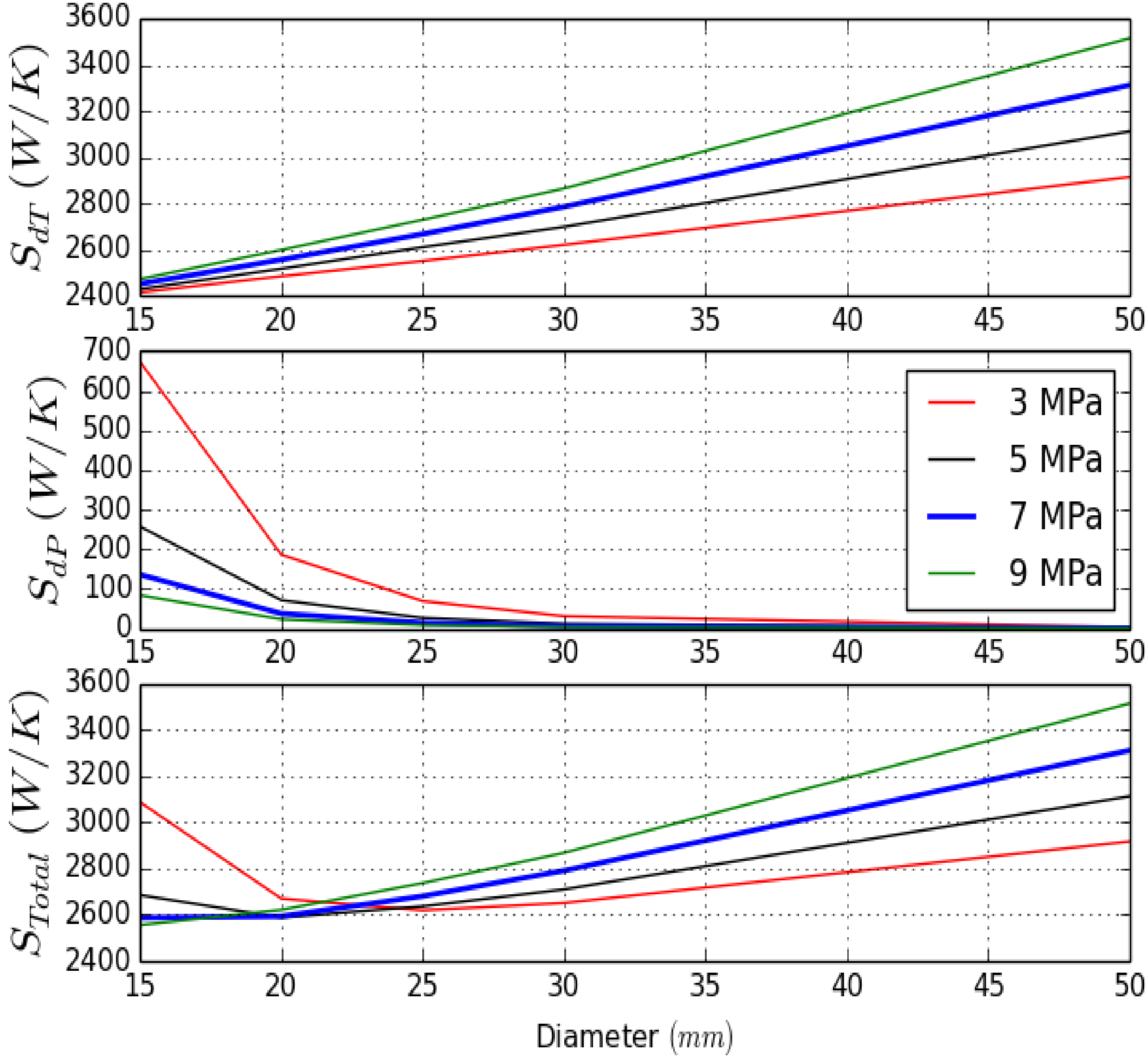


Results: Low mass flow



- $S_{gen,dT}$ = Finite Temperature differences
- $S_{gen,dP}$ = Fluid friction
- $S_{gen,dT}$ increases with increase in diameter
- $S_{gen,dP}$ decreases with increase in diameter
- $S_{gen,dP}$ small to negligible influence on the total entropy generation
- $S_{gen,dP}$ only influences smallest diameter at smallest operating pressure

Results: High mass flow



- $S_{gen,dT}$ = Finite Temperature differences

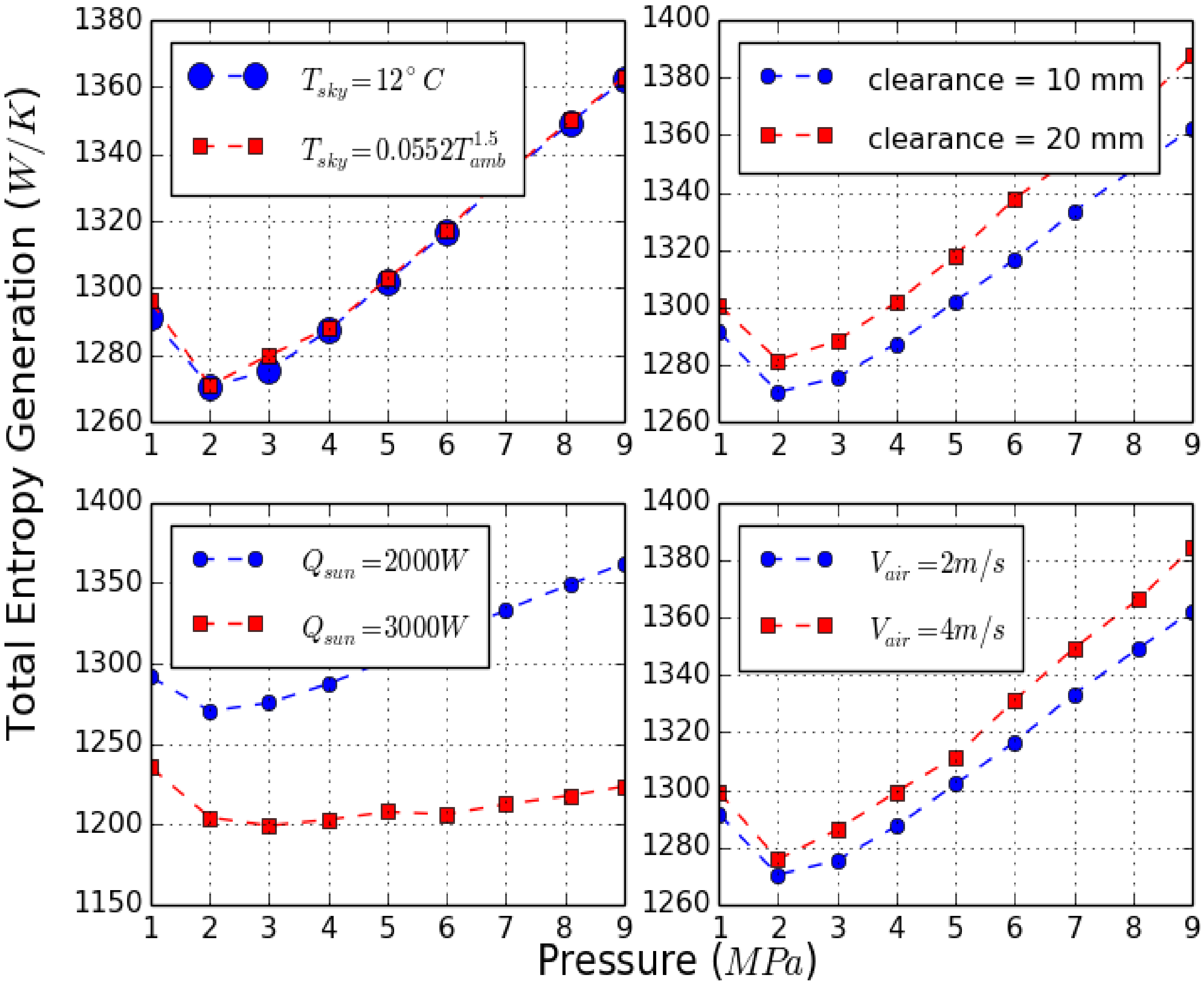
- $S_{gen,dP}$ = Fluid friction

- $S_{gen,dP}$ larger influence for the high mass flow rate case

- Higher $S_{gen,\,dP}$ values not only due to more fluid but due to fluid friction becoming significant for small diameters

- Effect noticeable for operating pressures 3 and 5 MPa

Sensitivity Analysis

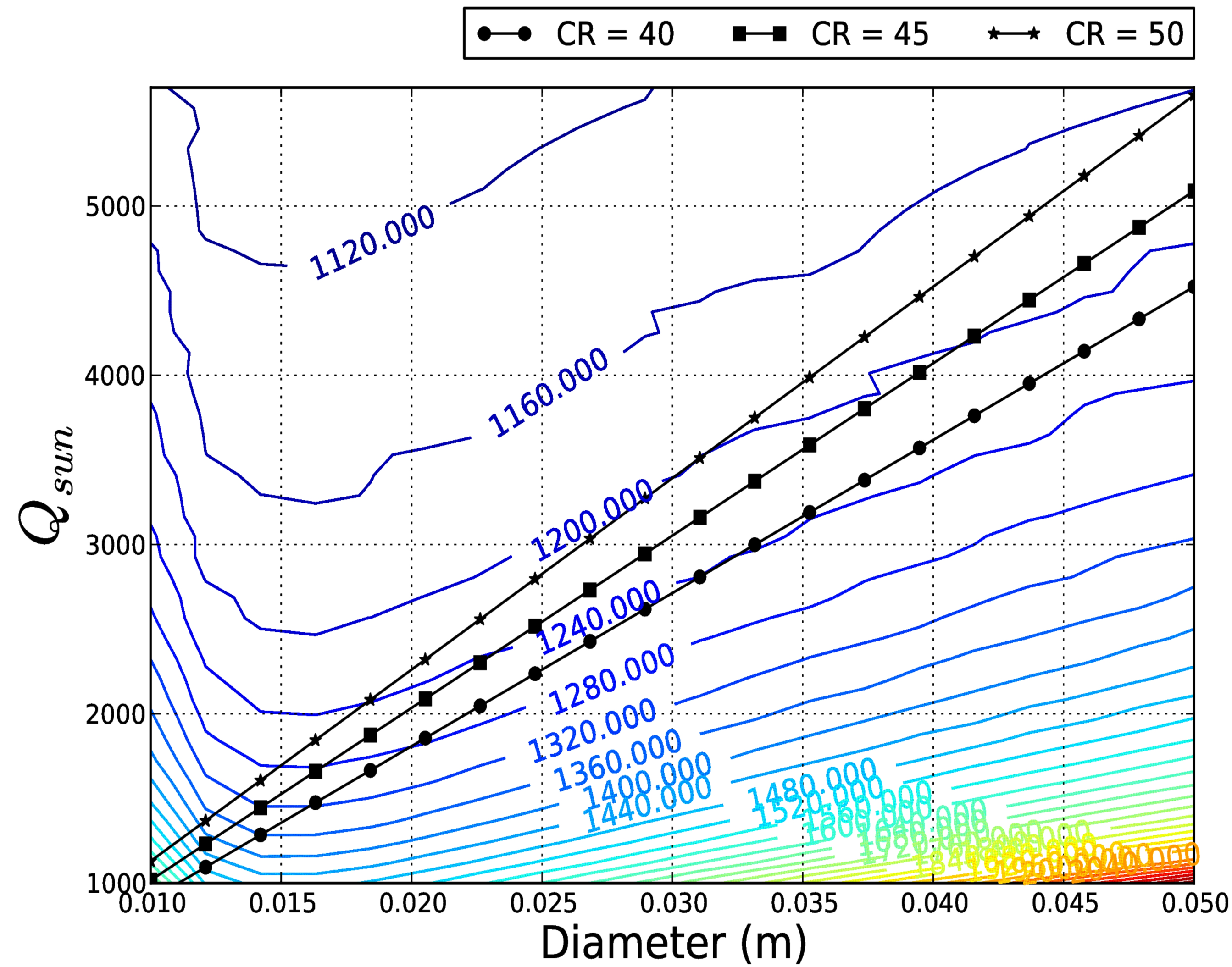


- Effective sky temperature minimal effect on S_{gen}

- Clearance and wind velocity only influences value of S_{gen} but not the minimum

- Q_{sun} shifts minimum

Optimisation



- CR (concentration ratio) constraint line
- 10 mm < D_i < 15 mm influences of fluid friction can be seen
- Di > 15 mm mostly influenced by $S_{gen, dT}$
- Higher CR means closer to optimality
- Constraint lines steeper than contour lines, if Q_{sun} and D_i increased S_{gen} can be lowered but effect diminishes for larger D_i

Case: T_{sat} = 250 °C (4 MPa), m = 0.2 kg/s

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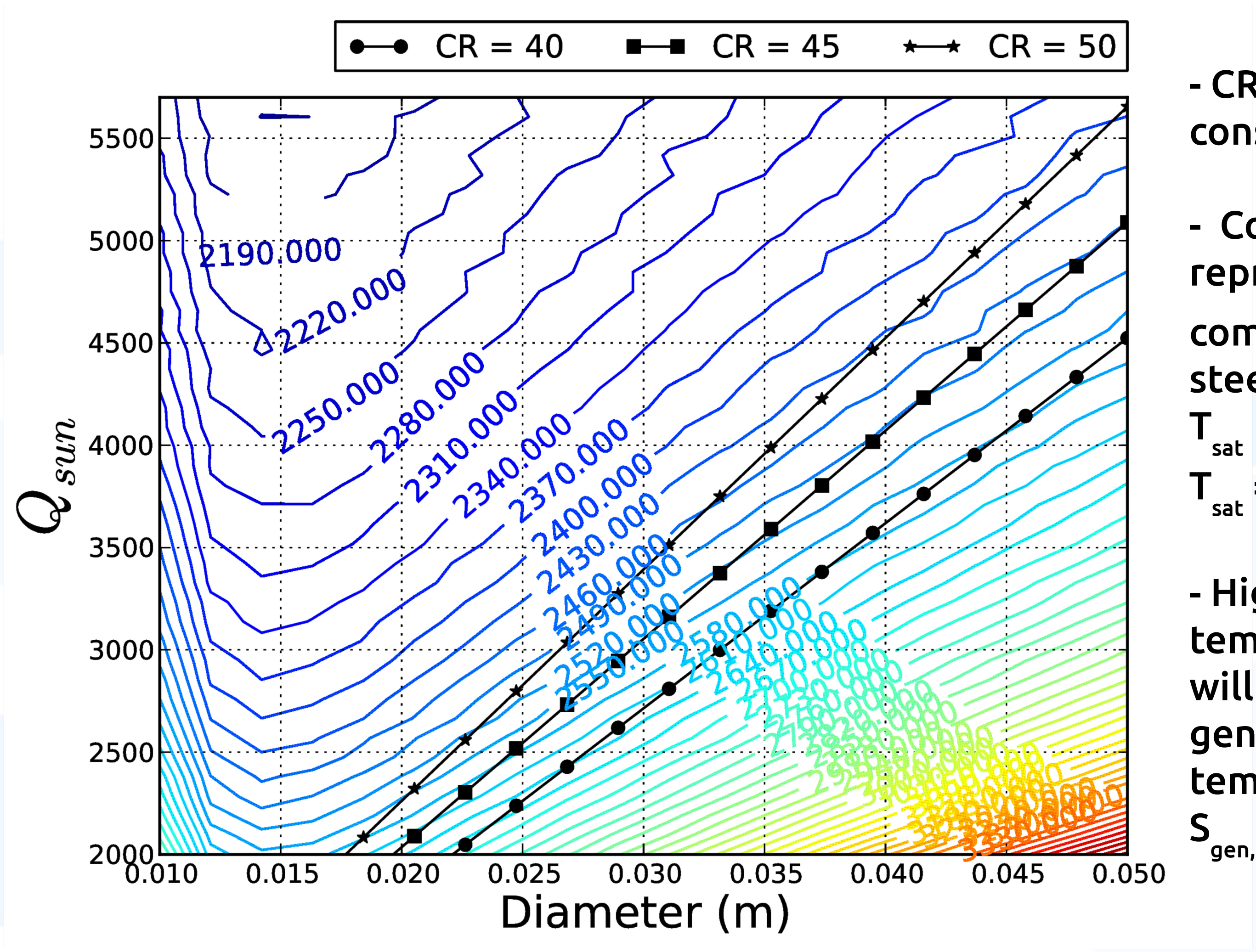
Optimisation



- CR (concentration ratio) constraint line
- Contour lines representing $S_{gen\ dT}$ component slightly steeper for case T_{sat} = 310 °C vs T_{sat} = 250 °C
- Higher temperatures and temperature differential will mean more entropy generation due to finite temperature differences $S_{gen,\ dT}$

Case: T_{sat} = 311 °C (10 MPa), m = 0.2 kg/s

Optimisation

Simulated Annealing (SA) Optimisation

- Function not entirely smooth
- SA doesn't use gradient information
- Available in Python (SciPy)
- Based on process of annealing molten metal

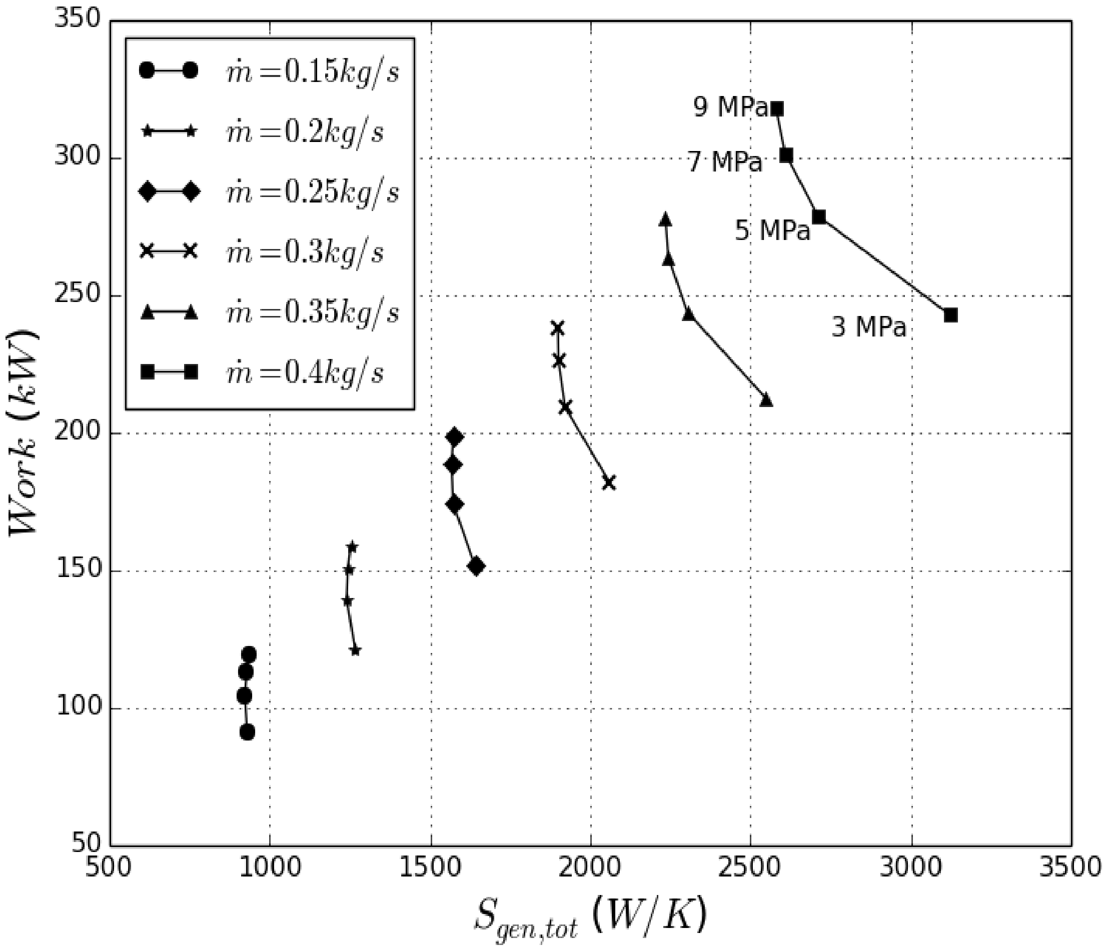
Table 1: Global Optimum

Parameter	Optimal
D_i	44.6 mm
Mass flow	0.1513 kg/s
Pressure	7.62 MPa
Total Entropy	899.14 W/K

Table 2: Optimal Pressure for various flow rates, Di = 20 mm

Mass flow (kg/s)	Optimal Pressure (MPa)	Total Entropy (W/K)
0.15	3.597	903
0.2	3.815	1211
0.25	3.948	1523
0.3	4.68	1838
0.35	5.47	2156
0.4	6.715	2478

Multi-Objective Optimisation



- Higher mass flow; more work output

- Higher mass flow rate is influenced by $S_{gen\ dP}$ at lower operating pressures (3 and 5 MPa)

- Lower mass flow rates (0.15 kg/s) hardly influenced by $S_{gen\ dP}$

- Outcome will change for other cases where tube diameters are larger

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Case: D_i = 15 mm

Conclusions

- Two-phase region long for low operating pressure

Higher Enthalpy of Evaporation

3 MPa: h_{fg} = 1796 kJ/kg VS 9 MPa: h_{fg} = 1379 kJ/kg

- Long two-phase regions result in larger contributions from $S_{gen, dP}$

- For most cases $S_{gen, dT}$ contributes more significantly to the total entropy generation

(Especially at diameters larger than 20 mm and when concentration ratio constraints are taken into account)

- Larger concentration ratios result in less entropy generation

- If Q_{sun} is constant it will always be more advantageous to consider smaller diameters

- If the CR is kept constant increasing the diameter will tend to decrease S_{gen}

Conclusions

- Simulated Annealing optimisation

- Optimal Operating pressure increases if mass flow rate is increased

- Higher operating pressures slightly increase S_{gen} but are more advantageous because more available work

- Operating pressures lower than 3 MPa is not recommended due to large $S_{gen, dP}$ contributions and excessive and small work output

Future Work

- Heat transfer enhancement
- Cost Analysis

Thank You