Power required for CO_2 capture and storage on the case ship

Program of hydrostatics and power prediction for cargo ships by Holtrop- 1988 method using free ship 3_37+ software:

Project: Emma Maersk
Designer : T M Rabiul Islam
File name: FREE! ship emma . fbm
Design length : 376.00 m
Design beam : 56.400
Design draft : 15.500 m
Midship location : 188.00 m
Water density : 1.025 t/m^3
Appendage coefficient : 1.0000
Date:21/03/2012
Time:19:41:46

Hydrostatics and Brake power:

Draft (m)	Speed (knots)	Displacement (tonnes)	Brake power (kW)
14.50	21.00	220636	34400.00
15.00	21.00	230135	34500.00
15.50	21.00	239753	34600.00

Voyage days:

Distance of the voyage Balboa, Panama to Nagoya, Japan

$$Voyage_{Distance} := 7825nmi$$

$Ship_{Speed} := 21knot$ [i]

Actual voyage days

$$Voyage_{Days} := \frac{Voyage_{Distance}}{Ship_{Speed} \cdot day} = 15.53$$

Assumed voyage days considering rough weather

$$Voyage\_Days := 18$$

[i]. Reference value from Marine traffic.com

Fuel consumption and CO_2 emissions:

Draft at 14.50m $Draft_x := 14.50m$

Draft at 15.50m $Draft_y := 15.50m$

Power at draft 14.50m $Power_x := 3.44 \times 10^4 \text{ kW}$

Power at draft 15.50m $Power_y := 3.46 \times 10^4 \text{ kW}$

Displacement at draft 15m $Disp_0 := 2.301 \times 10^5 \text{tonne}$

Displacement at draft 14.50m $Disp_x := 2.206 \times 10^5 \text{tonne}$

Displacement at draft 15.50m $Disp_y := 2.397 \times 10^5 \text{tonne}$

Percentage of the CO_2 capture from total $\mu := 0.20$

Brake specific fuel consumption $BSFC := 0.171 \frac{kg}{kW \cdot hr}$ [ii]

Brake specific CO_2 emissions $BSCO_2 := 0.620 \frac{kg}{kW \cdot hr}$ [ii]

Selected draft calculated using basic linear interpolation y = mx+c

$$Draft_0 := \frac{(Draft_y - Draft_x)}{Disp_y - Disp_x} \cdot (Disp_0 - Disp_x) + Draft_x = 15\,m$$

Selected power at draft 15m calculated using basic linear interpolation y = mx+c

$$Power_0 := \frac{(Power_y - Power_x)}{Draft_y - Draft_x} \cdot (Draft_0 - Draft_x) + Power_x = 3.45 \times 10^4 \cdot kW$$ [iii]

[ii]. Wartsila RT-flex96C engine Manual

[iii]. Power selected at draft 15m and used the interpolation to create Mathcad loop for calculation.

Fuel consumption's at draft 15m

$$FC_0 := BSFC \cdot Power_0 \cdot 24 \cdot hr = 141.59 \cdot tonne$$

20% of CO_2 emissions at draft 15m

$$CO2_0 := BSCO_2 \cdot Power_0 \cdot 24 \cdot hr \cdot \mu = 102.67 \cdot tonne$$

$$ORIGIN := 1$$

Fuel consumption and CO_2 emissions :

$$
Calc := \left|
\begin{array}{l}
Disp_1 \leftarrow Disp_0 \\
Draft_1 \leftarrow Draft_0 \\
Power_1 \leftarrow Power_0 \\
FC_1 \leftarrow FC_0 \\
CO2_1 \leftarrow CO2_0 \\
days \leftarrow Voyage\_Days \\
\text{for } j \in 2 .. days \\
\quad \left|
\begin{array}{l}
Disp_j \leftarrow Disp_{j-1} - FC_{j-1} + CO2_{j-1} \\
Draft_j \leftarrow \dfrac{(Draft_y - Draft_x)}{Disp_y - Disp_x} \cdot (Disp_j - Disp_x) + Draft_x \\
Power_j \leftarrow \dfrac{(Power_y - Power_x)}{Draft_y - Draft_x} \cdot (Draft_j - Draft_x) + Power_x \\
FC_j \leftarrow BSFC \cdot Power_j \cdot 24 \cdot hr \\
CO2_j \leftarrow (BSCO_2 \cdot Power_j \cdot 24 \cdot hr \cdot \mu)
\end{array}
\right. \\
\left(\dfrac{Disp}{tonne} \quad \dfrac{Draft}{m} \quad \dfrac{Power}{kW} \quad \dfrac{FC}{tonne} \quad \dfrac{CO2}{tonne} \right)
\end{array}
\right.
$$

$$Calc = (\{18,1\} \quad \{18,1\} \quad \{18,1\} \quad \{18,1\} \quad \{18,1\})$$

$Disp := Calc_{1,1} \cdot tonne$

$Draft := Calc_{1,2} \cdot m$

$Power := Calc_{1,3} kW$

$FC := Calc_{1,4} \cdot tonne$

$CO_2 := Calc_{1,5} \cdot tonne$

$i := 1 .. Voyage\_Days$

$Days_i := i - 1$

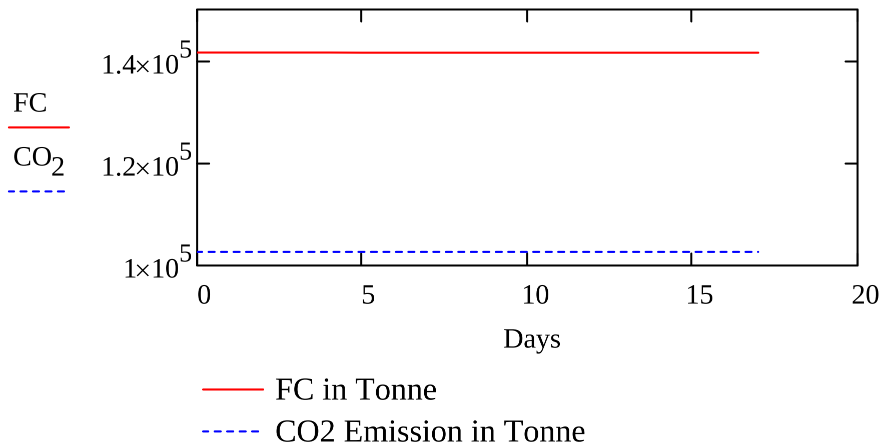


Figure 0-1: Fuel consumption VS CO_2 emissions in Respective Days

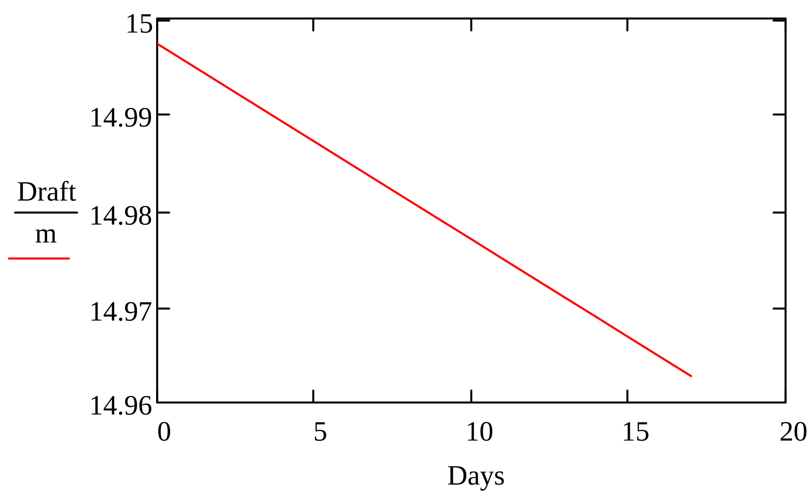


Figure 0-2: Draft VS Respective Days

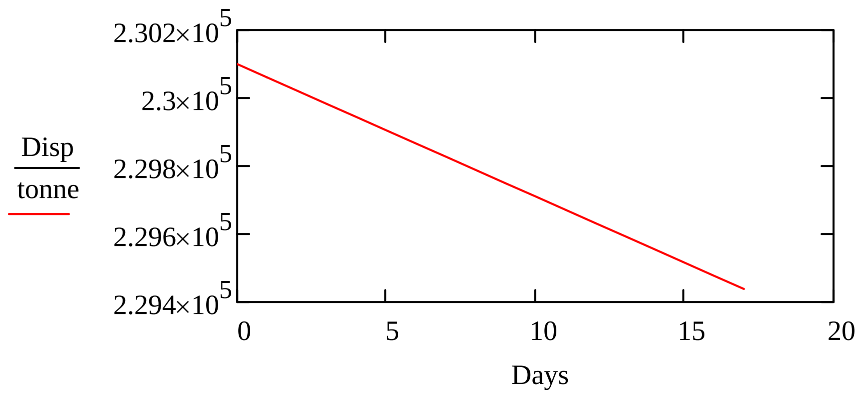


Figure 0-3: Displacement VS Respective Days

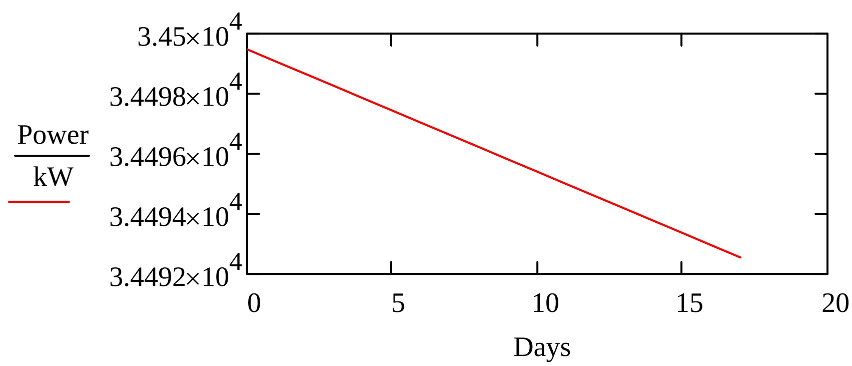


Figure 0-4: Power VS Respective Days

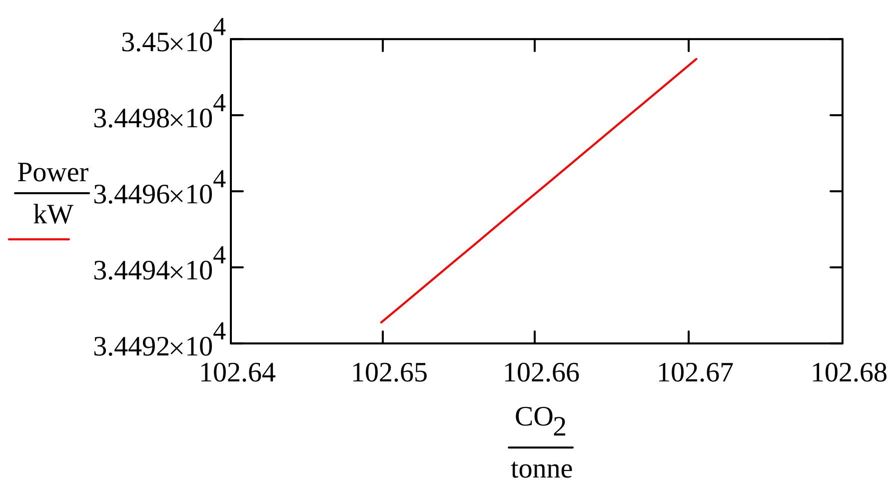


Figure 0-5: Power VS CO_2 Emissions

$ix := 1 .. Voyage\_Days - 1$

$Total\_FC := \sum FC$

Total Fuel consumption at 18days voyage

$$Total\_FC = 2.55 \times 10^{3} \cdot tonne$$

20% of the total CO_2 emissions in 18days voyage

$$Total\_CO2 := \sum CO_2 = 1.85 \times 10^{3} \cdot tonne$$

Day 9 selected for the calculation as it is average of 18 days voyage

20% of the total CO_2 emissions at day9

$$CO_{2_9} = 1.03 \times 10^{5} \cdot kg$$

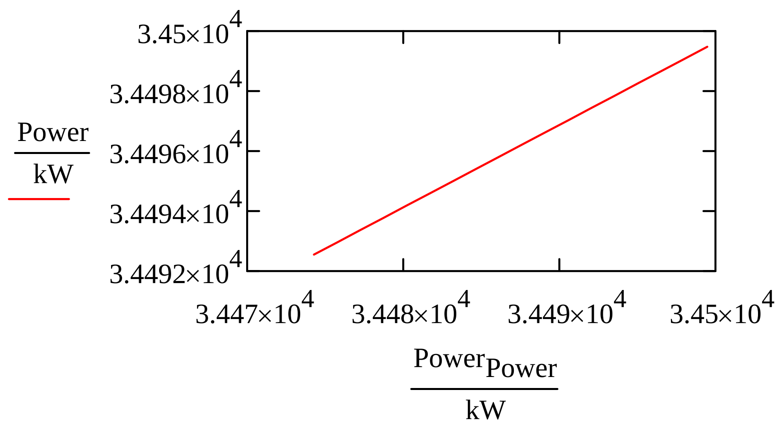
<u>Transportation power for captured CO_2:</u>

$$
CalcPower := \left|
\begin{array}{l}
Disp_1 \leftarrow Disp_0 \\
Draft_1 \leftarrow Draft_0 \\
Power_1 \leftarrow Power_0 \\
FC_1 \leftarrow FC_0 \\
days \leftarrow Voyage\_Days \\
\text{for } j \in 2 .. days \\
\quad \left|
\begin{array}{l}
Disp_j \leftarrow Disp_{j-1} - FC_{j-1} \\
Draft_j \leftarrow \dfrac{(Draft_y - Draft_x)}{Disp_y - Disp_x} \cdot (Disp_j - Disp_x) + Draft_x \\
Power_j \leftarrow \dfrac{(Power_y - Power_x)}{Draft_y - Draft_x} \cdot (Draft_j - Draft_x) + Power_x \\
FC_j \leftarrow BSFC \cdot Power_j \cdot 24 \cdot hr
\end{array}
\right. \\
\left(\dfrac{Disp}{tonne} \quad \dfrac{Draft}{m} \quad \dfrac{Power}{kW} \quad \dfrac{FC}{tonne} \right)
\end{array}
\right.
$$

$Power_{Power} := CalcPower_{1,3} kW$

$ix := 1 .. Voyage\_Days - 1$

Power, the normal power and $Power_{Power}$ the power with captured CO_2



Power at day 9:

$$Power_9 = 3.45 \times 10^4 \cdot kW$$

Power with Captured CO_2:

$$Power_{Power_9} = 3.45 \times 10^4 \cdot kW$$

Transportation power at day 9:

$$Transportation_{Power_9} := Power_9 - Power_{Power_9} = 8.6 \cdot kW$$

Additional Power required of CO_2 capture and storage for case ship

According to the requirements of capture system for case ship it is require SOx scrubber system as well as membrane. Power requirement of both systems are given below:

Power required for SOx scrubber :

Power consumption for SOx scrubber $\phi := 0.01$ [iv]

Scrubbed power at day 9 $Power_9 = 3.45 \times 10^4 \cdot kW$

Required power for the SOx scrubber

$$Power_{SOx} := Power_9 \cdot \phi = 344.96 \cdot kW$$

Required power for the compression at capture :

According to the requirements of membrane capture system, the pressure of exhaust gas needs to the increased to get the continuous flow through the membrane as well as to redu the engine back pressure.

Mass flow of the exhaust gas $Mass_{flow} := 269.53 \frac{tonne}{hr}$ [v]

25% of the exhaust gas flow for calculation $\varphi := 0.25$

Mass flow rate of the exhaust gas towards compressor

$$m := Mass_{flow} \cdot \varphi = 18.72 \frac{kg}{s}$$

[iv].Understanding exhaust gas treatment systems for ship owners and operators, Lloyds register, June 2012]

[v].Wärtsilä RT-flex96-B Marine Engine Manual, October 2012

Assumed temperature of the exhaust gas after scrubber (70°C), $T_1 := 343 \cdot K$

<u>Compression power:</u>

Assumed, the compressor works in adiabatic process.

Heat capacity ratio of exhaust gas $\gamma := 1.294$ [vi]

Exhaust gas pressure after scrubber $P_1 := 1\text{bar}$

Required pressure for the membrane $P_2 := 1.5\text{bar}$

Delivery Temperature of the compressor

$$T_2 := T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 376.1\,K$$

Individual gas constant for CO_2 $R := 189 \frac{J}{kg \cdot K}$

Mechanical efficiency of the compressor $\eta m := 0.85$

Indicated power of compressor

$$IP := \frac{\gamma}{\gamma - 1} \cdot m \cdot R \cdot \left(T_2 - T_1\right) = 515.36 \cdot kW$$

Required input power for the compressor

$$Compressor_{Power} := \frac{IP}{\eta m} = 606.31 \cdot kW$$

Required power for capture:

As membrane do not required any power only required the pressure so,

Power for the capture = (Power SOx scrubber+ Power compressor) = 951.41 kW

[vi]. γ value calculated according to the percentage of exhaust gas constituents.

Required power calculation for liquid phase

To economically transport and store the onboard captured CO_2 it is required to convert either solid or liquid phase. This is because gaseous phase of CO_2 has the less density tha that of solid or liquid. According to the fig:2-11, CO_2 phase diagram, Temperature -50°C (223° K) and Pressure 5.5 bar needed to make liquid phase. As a result, CO_2 needed to be compressed which helps to increase the pressure of it and in the refrigeration system temperature become decreased.

<u>Compression power:</u>

20% of the captured CO_2 at day 9 $\quad Mass := 1.03 \times 10^{5}\ kg$

Mass flow rate of captured CO_2 $\quad m_1 := 1.19 \frac{kg}{s}$

The CO_2 gas pressure after membrane $\quad P_1 := 1bar$

Required pressure for the liquid phase $\quad P_3 := 5.5bar$

Delivery temperature for compressor at compression

$$T_3 := T_2 \cdot \left(\frac{P_3}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 554.01\,K$$

Heat capacity ratio of CO_2 $\quad \gamma := 1.281$

Indicated power of the compressor

$$IP := \frac{\gamma}{\gamma - 1} \cdot m_1 \cdot R \cdot \left(T_3 - T_2\right) = 182.41 \cdot kW$$

Required power for the compressor at compression

$$Compressor_{Power} := \frac{IP}{\eta m} = 214.6 \cdot kW$$

[vii]. Assumed 0.5 bar pressure loss in membrane capture system

Required power for refrigeration system

Temperature of the CO_2 after compressor $T_3 = 554.01\,K$

For converting joule to kilo joule $k := 1000$

Specific heat capacity of CO_2 at 550° K $cp := 1.046\,\frac{k\cdot J}{kg\cdot K}$

Required temperature for liquid phase $T_4 := 223K$

Change in temperature

$$\delta t := T_4 - T_3 = -331.01\,K$$

Latent heat of vaporization $L_{Vap} := 574\,\frac{k\cdot J}{kg}$

Required heat transfer

$$Q := m_1\cdot cp\cdot \delta t + m_1\cdot L_{Vap} = 271.04\cdot kW$$

Efficiency of heat transfer $\eta_{ht} := 0.85$

Desired heat removal

$$Q_L := \frac{Q}{\eta_{ht}} = 318.87\cdot kW$$

Coefficient of the performance $COP_R := 3.5$ [viii]

Required power input for the refrigeration system

$$W_{Refrigeration} := \frac{-Q_L}{COP_R} = -91.11\cdot kW$$

Power required for liquid phase: Compression power + Refrigeration power = 305.71kW

[viii]. Assumed reference value thermodynamics an Engineering Approach page, 313

Required power for solid phase **:**

According to the CO_2 phase diagram (fig:2-11), temperature -78.5°C (194.65° K) and pressure 1 bar is required to get the solid phase which will only be used in refrigeration system.

Latent heat of fusion $L_{Fusion} := 184 \cdot \frac{k \cdot J}{kg}$

Specific heat capacity of CO_2 $cp_{gas} := 0.918 \cdot \frac{k \cdot J}{kg \cdot K}$

Required temperature for solid phase $T_5 := 194.65K$

Change in temperature for solid phase

$$\delta t_{Solid} := T_5 - T_2 = -181.45\,K$$

Required heat transfer

$$Q := m_1 \cdot cp_{gas} \cdot \delta t + m_1 \cdot L_{Fusion} = -142.64 \cdot kW$$

Efficiency of heat transfer $\eta_{ht} := 0.85$

Desired heat removal

$$Q_L := \frac{Q}{\eta_{ht}} = -167.81 \cdot kW$$

Coefficient of the performance of refrigerator $COP_R := 3.5$

Required power input for solid phase

$$W_{Solid} := \frac{Q_L}{COP_R} = -47.95 \cdot kW$$

From the above calculation it shows that liquid phase requires more power than the solid phase as such to get the required pressure by the compressor the temperature normally increased, as a result more power necessary for cooling down CO_2 .

Number of container and power required to store the captured CO_2

$ORIGIN := 1$

Amount of CO_2 daily

$iy := 1 .. Voyage\_Days$

$$CO_{2daily_{iy}} := \sum_{x=1}^{iy} CO_{2_x}$$

$CO_{2daily} =$

	1
1	102.67
2	205.34
3	308.01
4	410.67
5	513.34
6	616
7	718.67
8	821.33
9	923.99
10	$1.03 \cdot 10^3$
11	$1.13 \cdot 10^3$
12	$1.23 \cdot 10^3$
13	$1.33 \cdot 10^3$
14	$1.44 \cdot 10^3$
15	$1.54 \cdot 10^3$
16	$1.64 \cdot 10^3$
17	$1.75 \cdot 10^3$
18	$1.85 \cdot 10^3$

$\cdot tonne$

Number of container required daily

$Container_{Capacity} := 30tonne$

$$Cont\_No_{iy} := \frac{CO_{2daily_{iy}}}{30tonne}$$

$Cont\_No_{iy} =$

3.42
6.84
10.27
13.69
17.11
20.53
23.96
27.38
30.8
34.22
37.64
41.07
44.49
47.91
51.33
54.75
58.17
61.6

<u>Required power to store the container in allowable temperature:</u>

Required heat transfer: $Q := 40\frac{kcal}{hr} = 46.52\,W$ [ix]

Required heat transfer at day

$Q_{day_{iy}} := Cont\_No_{iy} \cdot Q \cdot 24$

$Q_{day_{iy}} =$

3.82
7.64
11.46
15.28
19.1
22.93
26.75
30.57
34.39
38.21
42.03
45.85
49.67
53.49
57.31
61.13
64.95
68.77

$\cdot kW$

Required heat transfer for container at one day $Q := 3.82kW$

Efficiency of the heat transfer $\eta_{ht} := 0.85$

Desired heat removal $Q_L := \frac{Q}{\eta_{ht}} = 4.49 \cdot k \cdot W$

Required power input to store the container

$$W_{Store} := \frac{Q_L}{COP_R} = 1.28 \cdot k \cdot W$$

[ix]. www.seacoglobal.com/26000+litre+T11+W

Additional Power required of CO_2 capture and storage for case ship:

Capture power+Transportation+ Compression+Refrigeration+Container store) = 1267.05 kW

$$Power_{day_9} := 3.45 \times 10^4 \ kW$$

$$Addiotionl_{Power} := 1267.05kW$$

$$Req_{Power\%} := \frac{Addiotionl_{Power} \cdot 100}{Power_{day_9}} = 3.67$$

Additional power required for the considered CO_2 capture and storage for case ship is 3.67% of the engine power.