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Exam question begins

You are designing an anchor-handling tug-supply (AHTS) vessel with an icebreaking bow and a design icebreaking capability of 4 knots in 1.2 m level ice in first-year level ice with a flexural strength of 500 kPa.

The hull is 100 metres long at the waterline, has a beam of 20 metres, and draught of 7 metres. The average waterline opening angle is 35° and average hull vertical angle 25°. The vessel has two controllable pitch propellers with a diameter of 4.2 metres.

Hull-ice friction coefficient is 0.1 and the density difference between sea water and ice 125 kg/m³.

Your hydrodynamic engineer has provided you the following open water speed-power curve:

Speed [knots]	8	11	14	17	20
Propulsion power [kW]	1000	4000	9000	16000	25000

Determine the following:

- minimum installed propulsion power required to meet the desired icebreaking capability (2 points);
- vessel's h-v-curve with this power (3 points); and
- ice thickness where the vessel can achieve a speed of 10 knots.

(exam question ends)

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Model answer

The student is expected to be familiar with how h-v-curve is determined and the meaning of different vessel properties used in these calculations.

The calculated Lindqvist components are the following:

Ice thickness [m]	Crushing [kN]	Bending [kN]	Submersion [kN]
0.2	6	6	57
0.4	25	18	115
0.6	56	32	172
0.8	99	50	230
1.0	154	70	287
1.2	222	92	344
1.4	302	116	402
1.6	395	141	459

First, let's determine the ice resistance in 1.2 m ice at a speed of 4 knots (≈ 2.06 m/s):

$$R_{ice}(v) = (222\text{ kN} + 92\text{ kN})\left(1 + 1.4\frac{2.06\,\frac{\text{m}}{\text{s}}}{\sqrt{9.81\,\frac{\text{m}}{\text{s}^2} \times 1.2\text{ m}}}\right) + 344\text{ kN} \times \left(1 + 9.4\frac{2.06\,\frac{\text{m}}{\text{s}}}{\sqrt{9.81\,\frac{\text{m}}{\text{s}^2} \times 100\text{ m}}}\right) \approx 1134\text{ kN}$$

In order to meet the icebreaking capability requirements, the propulsion power has to be sufficient to produce about 1134 kN of net thrust at a speed of 4 knots to overcome the additional resistance caused by ice.

Let's first calculate the bollard pull and net thrust using the open water speed-power curve values:

$$T_B = K_E \cdot (P_D \cdot D)^{\frac{2}{3}}$$

where $K_E = 0.98$.

$$T_{NET}(v) = T_B\left(1 - \frac{1}{3}\frac{v}{v_{ow}} - \frac{2}{3}\left(\frac{v}{v_{ow}}\right)^2\right)$$

Maximum open water speed [knots]	8	11	14	17	20
Propulsion power [kW]	1000	4000	9000	16000	25000
Bollard pull [kN]	255	643	1104	1620	2181
Net thrust (v=4 kn) [kN]	170	508	939	1433	1978

Based on the above, the propulsion power needed to produce 1134 kN of net thrust at a speed of 4 knots is somewhere between 9000 kW and 16000 kW. Let's use linear interpolation between these points to determine the sufficient propulsion power. This can be done analytically or graphically; latter presented on the following page. The result is 11500...12000 kW (analytically solved exact value

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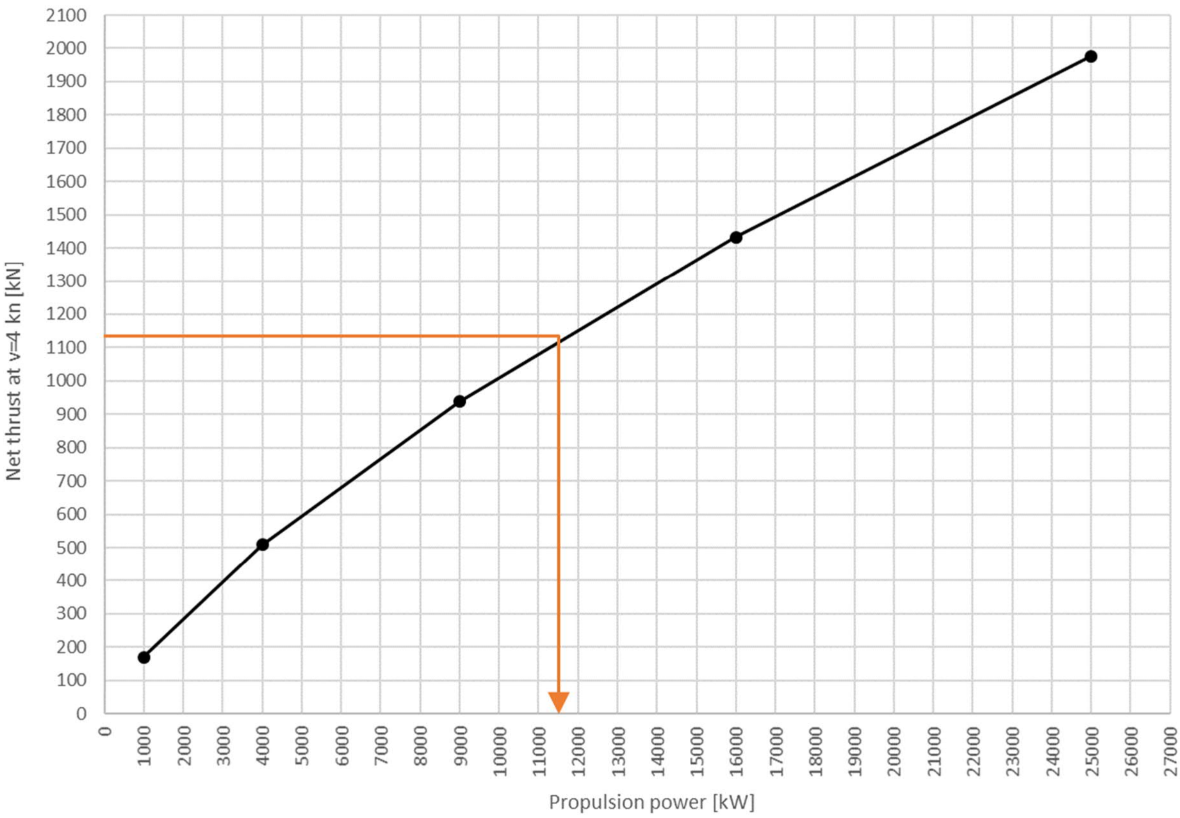
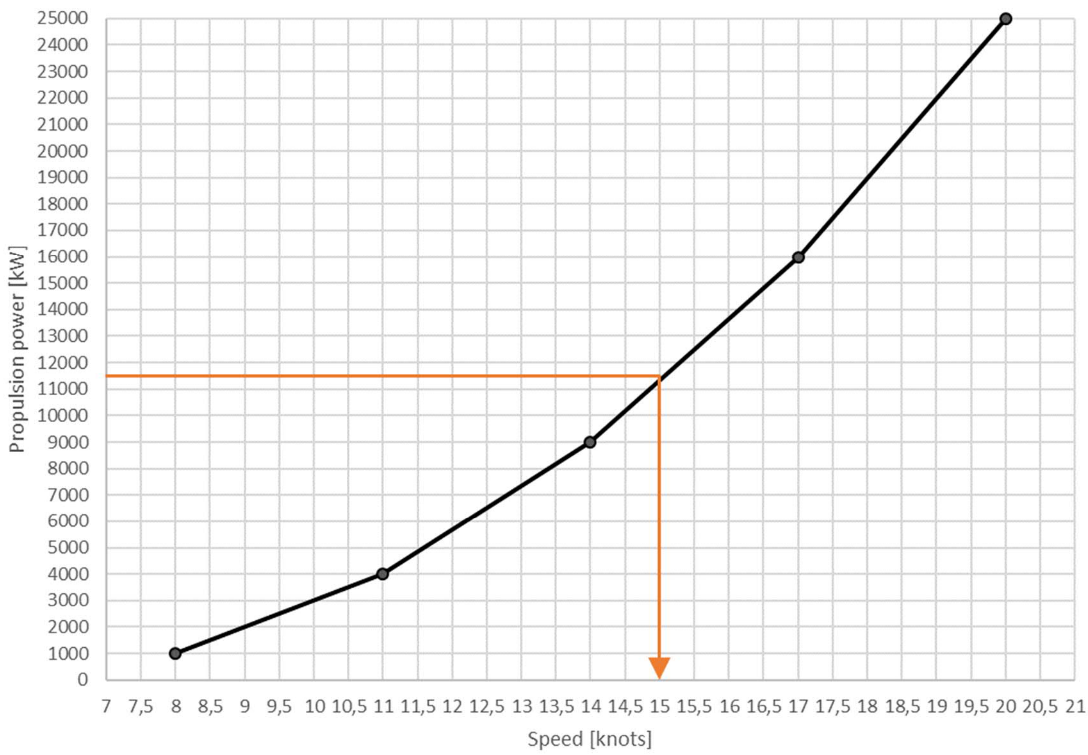
would be 11596 kW). The corresponding calculated bollard pull is 1300…1337 kN (analytical solution 1307 kN).

In order to calculate net thrust curve, we also need the corresponding speed in open water. For this, we can also use linear interpolation as shown on the following page. The corresponding open water speed is about 15…15.5 knots (analytical solution for 11596 kW would be 15.3 knots).





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Now we simply need to calculate the ice resistance as a function of speed (two points, e.g. 0 m/s and 8 m/s) and the net thrust as a function of speed, and determine the intersection points. The values are collected to the following two tables:

H_{ice}	R_{ice}(v=0 m/s)	R_{ice}(v=8 m/s)
0.2	70	307
0.4	157	672
0.6	260	1080
0.8	378	1524
1.0	511	2001
1.2	658	2509
1.4	820	3047
1.6	995	3613

Speed [m/s]	T_{NET} [kN] (analytical solution)
0	1307
1	1238
2	1140
3	1015
4	861
5	679
6	470
7	232
7.88 (15.3 kn)	0

The plotted graphs is shown on the following page. However, it is not necessary to include this graph in the final answer.

The intersection points can be solved analytically or graphically. The values are shown in the table and the final h-v-curve in the graph below (using analytical solutions).

H_{ice}	v [knots]
0.2	13.3
0.4	11.2
0.6	9.1
0.8	7.2
1.0	5.5
1.2	4.0
1.4	2.7
1.6	1.5

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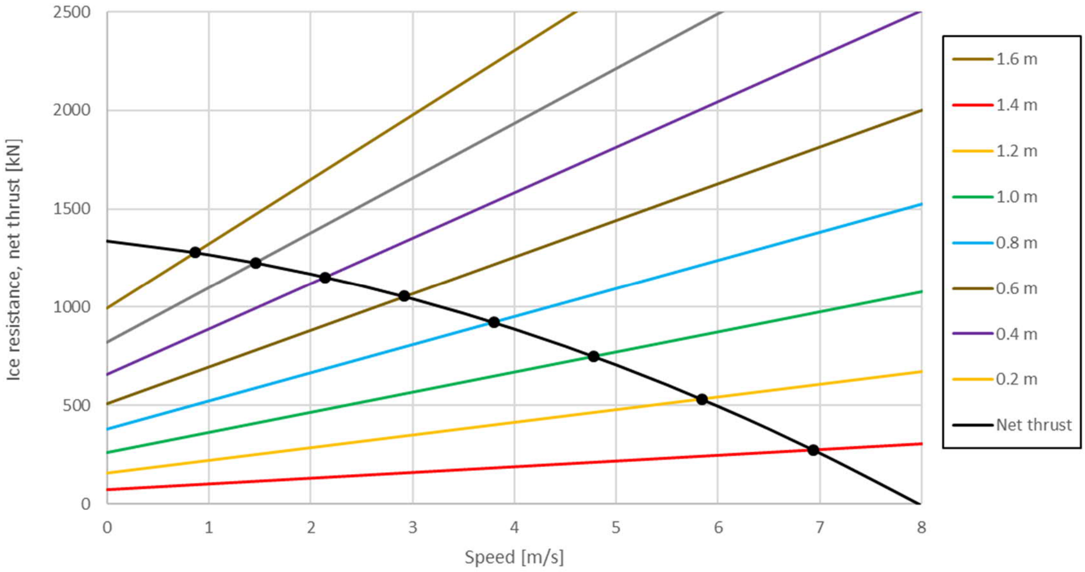
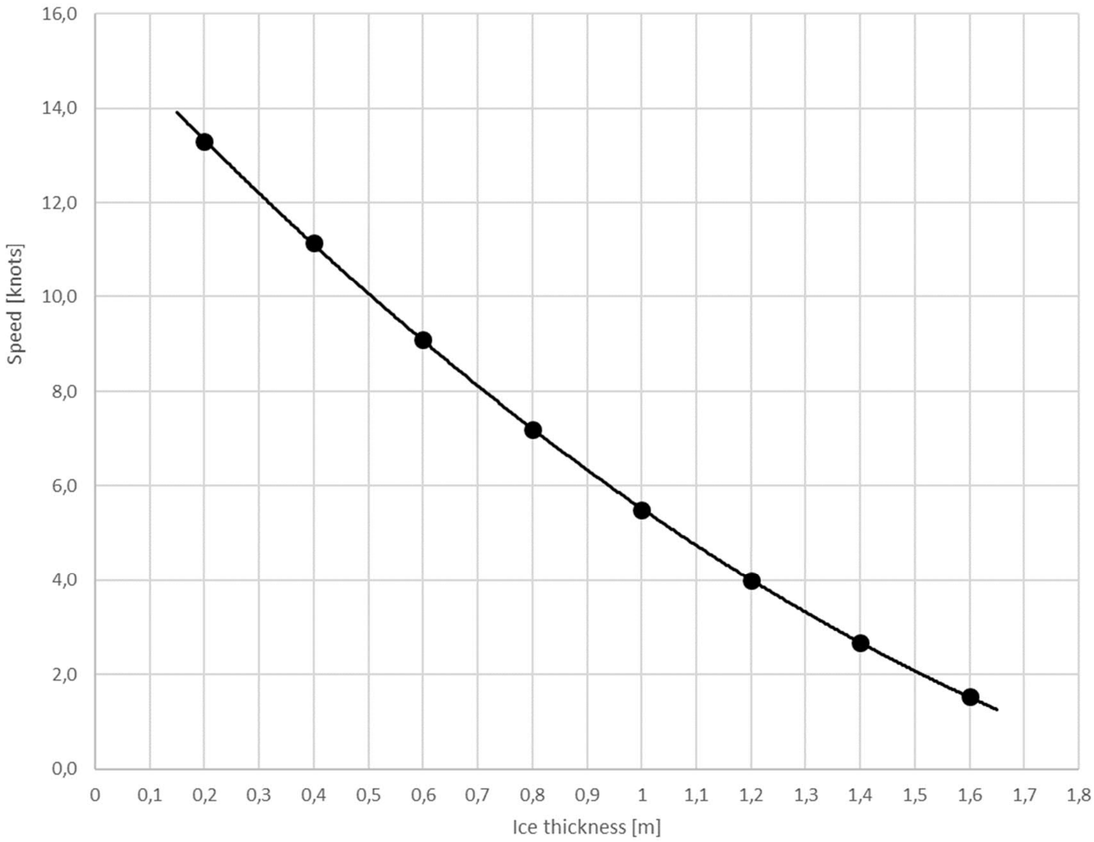


Final h-v-curve:



From the h-v-curve, we can read that the vessel can achieve a speed of 10 knots in about 0.5 m thick level ice.

Ideas for grading

- propulsion power (0, 1 or 2 points)
    - 2 points:
        - minimum propulsion power is determined by analyzing the open water speed-power curve and interpolating between given points as shown in the model answer
        - the target propulsion power should be around 11500…12000 kW and the corresponding open water speed between 15…15.5 knots
    - 1 point:
        - student has picked the minimum propulsion power without interpolating between the given points, but the selection is justified by calculating the ice resistance
        - student has used the correct method but there is a minor calculation error in e.g. ice resistance at the performance point
    - 0 points:
        - student has not done any analysis and has simply picked a propulsion power
        - there are multiple and/or major calculation errors
- h-v-curve (0…3 points)
    - 3 points
        - the values presented in the h-v-curve are reasonably close to the model answer (full points can be awarded if there is a calculation error in the previous part, but the h-v-curve has been developed correctly)
        - h-v-curve has correct shape (convex curve) and extends from "minimum speed" to "close to open water speed" without intersecting either axis
        - both "speed as a function of ice thickness" and "ice thickness as a function of speed" are acceptable
    - 2 points
        - there is a minor calculation error in ice resistance, net thrust etc. but the final h-v-curve is developed using the correct method
        - final h-v-curve is shown as a polygonal line (murtoviiva) instead of smoothed line (this is acceptable for intermediate linear interpolation plots which are not part of the final answer)
        - the final h-v-curve intersects x- or y-axis
        - final h-v-curve is missing labels (ice thickness and speed)
        - final h-v-curve is drawn significantly below the target performance point (4 knots in 1.2 m level ice) but the calculations are otherwise correct
    - 1 points
        - there are multiple calculation errors but the general methodology is still correct and some kind of final h-v-curve has been developed from the results
        - part of the question have been calculated correctly (e.g. ice resistance, net thrust) but the final h-v-curve has not been developed
    - 0 points
        - there are multiple and/or major calculation errors and the final h-v-curve has not been developed at all

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- performance point evaluation (0 or 1 points)
  - 1 point
    - ice thickness is read correctly from the h-v-curve (about 0.5 m)
    - points can be awarded even if there is a calculation error in the h-v-curve, but the value is read correctly
  - 0 points
    - answer is incorrect