A Case Study of Eenergy Analysis of Long Distance Squid Angling

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A fishing boat that fished offshore New Zealand and offshore Falkland Islands was subjected to analysis. A quantitative model which describes effect of CPUE (kg/h·line) on fuel unit (kl/kg) is proposed. This model shows that fuel unit depends strongly on CPUE when CPUE is small. In fishing grounds of small CPUE, fuel consumption by main engine occupied a large part of fuel unit, on the other hand, in fishing grounds of large CPUE, fuel consumption by auxiliary engines for refrigerators and fishing gears except fish lamps was dominant. Ratio of fuel consumption by fish lamps ranged from 10~20%. Average total fuel consumption per unit catch was $5.5_1 \times 10^{-4}$ kl/kg and average CPUE was 9.7₆ kg/h·line.

The fuel consumption of fishing is becoming one of the decisive factors in the economy of fisheries, because the fuel consumption per a kilogram of catch increased.¹⁾ In fisheries except fixed shore net fishing, fuel consumption gets around 80% to 90% of the total (direct and indirect) energy consumption and the proportion of fuel costs to the total costs is high.²⁾ To make designs for fuel saving, it needs to analyze quantitatively the important factors which affect on the fuel unit defined by the fuel oil consumed to produce a unit mass of catch (l of fuel oil per a kg of catch).

It has shown that, in squid angling fishery, the value of fuel unit divided by price (l/yen) is the highest among various fisheries and fuel costs amount for a half of total costs.²⁾ In squid angling fishery, the energy intensity gradually increased from 0.1 l/kg in 1957 to 0.3 l/kg in 1967 then it increased rapidly to 1.5 l/kg in 1974 and became stationary till 1983.* Its rapid increase might be brought by the development of new fishing grounds which are located very far from Japan, or use of brighter fishing lamps and decrease of squid resource might raise the energy intensity.

These make it difficult to analyze the energy intensity of squid angling fishery. On the other hand, squid angling fishery is a good subject for energy analysis of fishery because it is one of the most energy consuming fisheries as described above.

The present paper has dealt with a case study to analyze fuel consumption during squid angling of a Japanese fishing boat.

Methods

A fishing boat of 400-t class was subjected to the present case study. The boat was equipped with a 1800 PS main engine for use in navigation, the first and the second auxiliary engines of 310 PS (A₁ and A₂ engines) for use in actuating squid angling machines, a refrigerator to freeze squid, a refrigerator for a stock room, and other facilities, and the third auxiliary engine of 360 PS (A₃ engine) for use in lighting fish lamps. The boat had 36 double-line automatic squid angling machines, 20 single-line ones, and 138 fish lamps of 1 kW. The boat left Japan November 1984 and came back

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Table 1. Summarized data of fishing used in the present study

Phase	Period	Length of period (d)	Cruise time (h/d)	Number of lines (—)	Catch (10 ³ kg/d)	Fuel consumption			Operation time of A ₃ (h/d)	CPUE (kg/h·line)	I _f (l/kg)
						main engine (kl/d)	A ₁ +A ₂ (kl/d)	A ₃ (kl/d)			
Cruise	JP-NZ	23	21.9	0.0	0.0	2.80	0.560	0.0	0.0		
	NZ-FL	18	23.6	0.0	0.0	3.85	0.658	0.0	0.0		
	FL-JP	45	23.7	0.0	0.0	4.02	0.610	0.0	0.0		
	average	28.7	23.2	0.0	0.0	3.66	0.607	0.0	0.0		
Operation	NZ	39	7.05	63.5	3.83	0.757	0.994	0.338	9.06	3.54	0.868
	FL-1	20	6.02	54.3	14.7	0.707	1.36	0.361	9.17	12.0	0.488
	FL-2	19	3.19	44.7	16.7	0.316	1.36	0.443	10.9	11.2	0.450
	FL-3	16	2.19	42.7	19.9	0.183	1.50	0.569	13.8	15.0	0.436
	FL-4	11	2.73	55.0	18.5	0.344	1.39	0.545	12.6	10.5	0.446
	FL-5	14	4.18	66.3	10.1	0.455	1.28	0.558	13.6	5.54	0.550
	FL-6	13	7.69	64.9	4.72	1.05	1.15	0.485	12.0	3.54	0.892
	FL-7	17	9.59	67.2	1.94	1.37	0.933	0.513	10.9	1.72	1.77
	average	18.6	5.65	57.8	10.2	0.669	1.21	0.448	11.0	9.76	0.551
Others		56	9.90	0.0	0.0	1.44	0.774	0.0	0.0		

A₁: first auxiliary engine, A₂: second auxiliary engine, A₃: third auxiliary engine.

I_f: fuel consumption per unit mass of catch.

September 1985 after fishing in New Zealand waters and Falkland Islands waters.

The action of the boat was categorized in three phases: the cruise phase, the operation phase, and the others. In the cruise phase, the boat navigated using the main engine and one of the A₁ or A₂ engines. The navigation was classified in three periods: from Japan to New Zealand (JP-NZ), from New Zealand to Falkland Islands (NZ-FL), and from Falkland Islands to Japan (FL-JP). In the operation phase, the boat fished at eight different times. After every round of fishing, the catch was transhipped to a fish carrier. The interval to the next transshipment was called a period. The periods were NZ and FL-1 to FL-7. In the operation phase, the main engine was sometimes used for going after fish schools. We regarded the fishing time by the time when the main engine was not operated.

We read off in detail the time course of fuel consumption of every engine from the engineer's logbook and the daily quantity of fish catch from the report of fishing manager. Summarized data are presented in Table 1. These data were subjected to the analysis.

Results and Discussion

The fishing boat of this case study was operated as offshore New Zealand and at offshore Falkland

Islands. Therefore fuel consumption for the navigation between Japan and the fishing grounds should be very much larger than squid angling fishery in Japanese waters. However, if the resource of squid in New Zealand or Falkland Islands waters was enough larger than that in Japanese waters, the fuel unit could be less than that in Japanese waters. The overall fuel consumption of this boat was 836.77 kl and the total catch was 1517.5 ton, therefore the overall average fuel unit was 5.51×10^{-4} kl/kg. This value is only one thirds of 1.5×10^{-3} kl/kg which was the averaged value over all Japanese squid angling fishing at 1983.* Thus we can conclude that the cruise of the present boat was a favorable one from the view point of energy saving.

Fish Catch

During the whole operation, the fishing condition seemed to change with fishing season and the fishing grounds. The cumulative fish catch of each period is drawn against the cumulative fishing time in Fig. 1. The slope of a curve indicates the fishing rate. The curves of the first four periods in Falkland Islands waters, (FL-1 to FL-4) seemed to be indistinguishable with each other, and the slopes of them were larger than those of the other periods (NZ and FL-5 to FL-7). Since the number of lines used in each period did not differ much, the difference of slope can be

Fig. 1. Cumulative fish catch of each period against cumulative fishing time. NZ and FL-*i* denotes New Zealand waters and *i*-th period in Falkland waters.

Fig. 2. Percentage of fuel consumption of each engine in each phase.

interpreted to the difference of resource of squid.

From the comparison of slopes in Fig. 1, we can conclude that the resource of the first four periods in Falkland Island waters were around three times larger than that in New Zealand waters, and the resource of the last period was around a half of that in New Zealand waters. Therefore we can evaluate the effect of resource of fuel unit from comparison of fuel consumption of each period.

Fuel Consumption

Let us consider the fuel consumption of each engine in each phase. The percentages of fuel consumption were shown in Fig. 2. The fuel consumed in the cruise phase accounted for 43.8% of the total fuel, most part of this was consumed by the main engine. The amount of fuel consumed in the operation phase (41.4%) was comparable to that in the cruise phase, however the details of fuel consumption was different. The

Fig. 3. Correlation between daily operation time of main engine in operation phase and CPUE.

first and the second auxiliary engines consumed the largest part of fuel (21.5%) in the operation phase. The main engine consumed 11.9% of the total fuel even in the operation phase. According to the remarks of the engineer's logbook, the boat operated the main engine frequently to go after fish schools in the fishing grounds. The fuel consumption of fish lamps (A_3 engine) was 8.0% of the total fuel consumption. The fuel consumed in the other phase (14.8%) was not so large as those in the cruise phase or operation phase.

To investigate the detailed fuel consumption, we evaluated averaged values of daily fuel consumption rates for each period and phase (Table 1).

In the cruise phase, the daily fuel consumption rate was almost similar except JP-NZ. The smaller fuel consumption rate could be attributable to the smaller engine revolutions, 225 rpm in JP-NZ and 235 rpm in the other navigations, and also attributable to foulings of the boat. The daily fuel consumption rates of A_1 and A_2 engines in the cruise phase did not vary much and the average value was 0.607 k/d.

The fuel consumption rate in the operation phase was not so simple as that in the cruise phase. The daily fuel consumption rate of the main engine ranged from 0.183 k/d to 1.37 k/d depended on periods. Because the hourly fuel consumption rate was not varied much (8.34×10^{-2} k/h to 1.43×10^{-1} k/h, not shown in Table 1), the decisive factor of the daily fuel consumption rate of the main engine in the operation phase was the cruise time per a day. Since the main engine was used to go after fish schools in the operation phase, the cruise time per a day may depend on resource. In Fig. 3, we depicted the correlation between the

Fig. 4. Correlation between daily fuel consumption of A_1 and A_2 engines and daily catch rate. A_1 and A_2 engines were used to actuating squid angling machines, refrigerators and the other facilities except fish lamps.

daily operation time of the main engine and CPUE (catch per unit effort, kg/h·line). Evidently the daily operation time of the main engine showed negative correlation with CPUE, the correlation was described as;

$$t_j^m = 14.0 S_j^{-0.590} \quad (1)$$

($r=0.924$)

where t_j^m and S_j denote the daily operation time of the main engine of j -th period (h/d) and CPUE of the j -th period (kg/h·line). We should note on that this correlation is reflected from the decision of fishing manager. Therefore information about resource may affect on the results. Because this operation was the first operation in Falkland Islands waters, lack of such information might result the large fuel unit of FL-1.

The daily fuel consumption rates of A_1 and A_2 engines in the operation phase ranged from 0.933 kl/d to 1.50 kl/d. These values were larger than 0.607 kl/d which is the average fuel consumption rate in the cruise phase. Because the A_1 and A_2 engines were used for refrigerators and squid angling machines, fuel consumption rate of A_1 and A_2 engines in the operation phase may depend on fish catch. The daily fuel consumption rate were plotted against daily fish catch in Fig. 4. Positive correlation was obvious, the correlation was described as;

$$Q_j^a/M_j = 2.71 \times 10^{-5} (F_j/M_j) + 0.939 \quad (2)$$

($r=0.961$)

where Q_j^a , M_j , and F_j denote amount of fuel consumed by the A_1 and A_2 engines in the j -th period (kl), the length of the j -th period (d), and the total amount of fish catch in the j -th period (kg). Let us compare the value of slope, 2.71×10^{-5} kl/kg, with the net fuel consumption to freeze a kilogram of squid, which means the fuel consumption without considering the heat loss of the freezing room and stock room. When we assume the latent heat and the specific heat of squid to be 64 kcal/kg and 0.8 kcal/kg·K, the calorific value of fuel oil to be 9400 kcal/l,³⁾ the performance coefficient of refrigerators to be 2.0,⁴⁾ the freezing temperature and the water temperature to be -35°C and 10°C , the net fuel consumption per a kilogram of catch becomes 1.51×10^{-5} kl/kg. The observed value of 2.71×10^{-5} kl/kg was 1.79 times larger than the calculated net fuel consumption per a kilogram of catch. The excess of 1.20×10^{-5} kl/kg might be due to the operation of squid angling machines and the heat loss through the doors of the stock room because the air exchange rate through the doors is considered to be proportional to the catch rate.

The value of y-intercept of equation (2), 0.939 kl/d, is fairly larger than the average fuel consumption rate of A_1 and A_2 engines in the cruise phase, 0.607 kl/d. The difference, 0.332 kl/d, might be due to the heat loss though the walls of the freezing room and the stock room. When we divided the excess fuel consumption, 0.332 kl/d, by the average daily catch rate, 1.02×10^4 kg/d, we obtain 3.25×10^{-5} kl/kg for the contribution of this excess fuel consumption to the overall average fuel unit, this contribution amounted for 5.91% of the overall average fuel unit.

The daily fuel consumption rate of fish lamps (A_3 engine) changed from 0.338 kl/d to 0.569 kl/d corresponding to the change of lighting time per a day. When we use conversion factors of 2,450 kcal/kWh and 9,400 kcal/l³⁾ for electric power to heat energy and volume of fuel to heat energy, operation of 138 of 1 kW fish lamps for 11 hours per a day corresponds to consumption rate of 0.396 kl/d. This value was 12% smaller than the observed value (0.448 kl/d). Since A_3 engine and the associated generator was far smaller than the commercial power plant, it is natural that the observed fuel consumption was worth than the fuel consumption of the commercial power plant which has a conversion factor of 2,450 kcal/kWh.

As for the daily fuel consumption rate, we can conclude that in the cruise phase, the daily fuel consumption rates of the main and the A_1 and A_2 engines did not vary much in three navigations. In the operation phase, the daily fuel consumption rate of the main engine depended on CPUE, the daily fuel consumption rates of A_1 and A_2 engines depended on the daily fish catch, the daily fuel consumption rate of fish lamps depended on lighting time.

Fuel Unit

To scrutinize the effect of resource on the fuel unit, we evaluated the contribution of each engine of each phase in different period.

The contribution of all engines in the cruise phase for overall fuel unit, I^c (kl/kg), is

$$I^c = \frac{Q^c}{\sum_{j=1}^N F_j} \quad (3)$$

where Q^c denotes the total fuel consumption in the cruise phase (kl), and N denotes the number of periods. The value of I^c becomes 2.41×10^{-4} kl/kg in the present case.

The contribution of the main engine in the operation phase, I_j^m (kl/kg), is

$$I_j^m = \frac{Q_j^m}{F_j} \quad (4)$$

where Q_j^m denotes the fuel consumed by the main engine in the j -th period. The value of Q_j^m is described as;

$$Q_j^m = q_j^m \cdot t_j^m \cdot M_j \quad (5)$$

where q_j^m denotes the hourly fuel consumption rate of the main engine in the j -th period (kl/h). The fish catch in the j -th period, F_j (kg), can be expressed as a function of CPUE of the j -th period, S_j , as;

$$F_j = (24 - t_j^m) \cdot k_j \cdot S_j \cdot M_j \quad (6)$$

where k_j denotes the average number of fishing lines used in the j -th period (lines). Substitution of equations (1), (5), and (6) into equation (4) yields

$$I_j^m = \frac{q_j^m}{S_j \cdot k_j} \frac{1}{(24/14.0) \cdot S_j^{0.500} - 1} \quad (7)$$

The equation (7) shows that the contribution of the main engine in the operation phase to fuel unit, I_j^m (kl/kg), is a decreasing function with respect to CPUE, and also represents that I_j^m is proportional to the hourly fuel consumption rate

of the main engine, q_j^m , and is inversely proportional to the rate of fish catch, $S_j \cdot k_j$ (kg/h). The second term of the right hand side of equation (7) represents the effect of resource on I_j^m .

The contribution of the fuel consumption of A_1 and A_2 engines in the operation phase to fuel unit, I_j^a (kl/kg), is

$$I_j^a = \frac{Q_j^a}{F_j} \quad (8)$$

Substitution of equations (1), (2), and (6) into equation (8) yields

$$I_j^a = 2.71 \times 10^{-5} + \frac{6.71 \times 10^{-2}}{S_j \cdot k_j} \frac{S_j^{0.500}}{(24/14.0) \cdot S_j^{0.500} - 1} \quad (9)$$

The equation (9) represents that I_j^a is a decreasing function with respect to CPUE.

The fuel consumption by fish lamps (A_3 engine), Q_j^l (kl), is determined by the daily operation time of A_3 engine, t_j^l (h/d), as;

$$Q_j^l = q_j^l \cdot t_j^l \cdot M_j \quad (10)$$

where q_j^l denotes the hourly fuel consumption rate of A_3 engine (h/d). The contribution of fish lamps of j -th period, I_j^l (kl/kg), is

$$I_j^l = \frac{Q_j^l}{F_j} \quad (11)$$

Substitution of equations (1), (6), and (10) into equation (11) yields

$$I_j^l = \frac{t_j^l \cdot q_j^l / 14.0}{S_j \cdot k_j} \frac{S_j^{0.500}}{(24/14.0) \cdot S_j^{0.500} - 1} \quad (12)$$

It is obvious that I_j^l is a decreasing function with respect to CPUE. The contribution of fuel consumption in the others phase, I^o (kl/kg), is

$$I^o = \frac{Q^o}{\sum_{j=1}^N F_j} \quad (13)$$

where Q^o denotes the total fuel consumption in the others phase (kl). The value of the present case was 8.16×10^{-5} kl/kg.

Here we can describe the prediction equation of fuel unit of each period from CPUE as;

$$I_j = I^c + I^o + 2.71 \times 10^{-5} + \frac{1}{S_j \cdot k_j} \frac{1}{(24/14.0) \cdot S_j^{0.500} - 1} \{ (t_j^l \cdot q_j^l / 14.0 + 6.71 \times 10^{-2}) \cdot S_j^{0.500} + q_j^m \} \quad (14)$$

Let us substitute the overall averaged values for q_j^m , q_j^l , t_j^l and k_j : 0.118 kl/h, 4.07×10^{-2} kl/h, 11.0 h/d and 57.8 lines, and substitution of $2.41 \times$

Fig. 5. Effect of CPUE on fuel unit. Predicted curve from equation (15) and the observed data.

Fig. 6. Effect of CPUE on relative contributions of fuel consumption by main engine, fish lamps and the other facilities in operation phase.

10^{-4} kJ/kg and 8.16×10^{-5} kJ/kg into I^c and I^o yields

$$I_j = 3.50 \times 10^{-4} + 1.00 \times 10^{-3} \frac{S_j^{0.590} + 1.19}{S_j \cdot (S_j^{0.590} - 0.583)} \quad (15)$$

The observed values of I_j evaluated from division of the total fuel consumption of the j -th period by the catch of the j -th period followed by addition of I^c and I^o are listed in Table 1. The observed values of I_j are plotted against CPUE with the prediction curve by equation (15) in Fig. 5. The observed I_j decreased rapidly with increase of CPUE up to 5 kg/h-line, above 5 kg/h-line, I_j decreased gently with increase of CPUE. The equation (15) predicted the observed values fairly

well. The predicted curve rapidly decreased with increase of CPUE, and approached 3.50×10^{-4} kJ/kg. The representative value of CPUE in the Sea of Japan in 1984 and 1985 is 1.5 kg/h-line of which we evaluated as an average of data of regular observation,⁵⁻⁹⁾ assuming the average weight of squid is 0.25 kg. The predicted value of $I - I^c - I^o$ corresponding to 1.5 kg/h-line is 2.74×10^{-3} kJ/kg. Although the observed data of fuel unit in the Sea of Japan are not available, this predicted value is 1.83 times larger than 1.5×10^{-3} kJ/kg which is the average over all Japanese squid angling fishery in 1983.

Let us see how the predicted contributions of the main engine (I^m), of the A_1 and A_2 engines (I^a) and of the A_3 engine for fish lamps (I^l) depend on CPUE. The proportion of I^m , I^a and I^l with respect to $I^m + I^a + I^l$ are drawn with reference to CPUE in Fig. 6. The proportion of I^m to $I^m + I^a + I^l$, i^m (%), decreased with increase of CPUE, on the other hand, the proportion of I^a to $I^m + I^a + I^l$, i^a (%), increased with increase of CPUE. The proportion of I^l to $I^m + I^a + I^l$, i^l (%), did not depend much on CPUE. The value of i^a is greater than i^m when CPUE is larger than 2.2 kg/h-line. Fig. 6 indicates that when the resource is rich, energy saving in fishing gears and freezing systems are important to reduce fuel unit, when the resource is poor, energy saving in the navigation is important. Since fuel consumption by the main engine in the operation phase was reflected from the decision of fishing manager, development of a fishing information system is desired in Japanese waters.

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