Heat Transfer Coefficient between Ice Cover and Water in the Bohai Sea

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Abstract The calculative method of heat transfer coefficient between ice cover and water is analyzed considering the heat balance at ice cover bottom firstly. The heat transfer coefficient is calculated with the meteorological, oceanographic data and sea ice conditions measured on the JZ20-2 Oil/Gas Platform in the Bohai Sea during the winter of 1997/1998. From the results, it is shown that the heat transfer coefficient is smaller in the freezing and melting periods, which is about 0.16×10^{-3} an d 0.04×10^{-3} respectively. In the middle of ice season, the heat transfer coefficient has a larger value, which is about 0.5×10^{-3}. Lastly, the influences of ice thickness and ice type on the heat transfer coefficient are discussed. With the heat transfer coefficient determined above, the oceanic heat flux in the winter of 1997～1998 is calculated, and its trend in the winter is analyzed. This study can be referenced in the sea ice numerical simulation and prediction in the Bohai Sea.

Keywords sea ice, oceanic heat flux, heat transfer coefficient, bulk method

Introduction

In the study of sea ice numerical simulation, the oceanic heat flux is an important factor, which influences the ice thickness and the ice edge directly. Since the 1960s , a series of work has been conducted to determinate the oceanic heat flux in different ocean regions. In the previous studies, several methods have been established to determine the oceanic heat flux as follows: the eddy-correlate method (Mcphee, 1987; Maykut, 1986; Wettlaufer, 1991), the bulk model formulation (Omstedt and Wattlaufer, 1992; Moore, 1988; Josberger, 1987), the residual method (Shirasawa, Ingram and Hudier, 1997; Omstedt and Wattlaufer, 1992; Lytle and Ackley, 1996; Harvey, 1990; Tang, 1991) and the sensitivity analysis method (Parkinson and ishington, 1979; Wang et al., 1984; Lu, 1987). The oceanic heat flux is controlled by the transport capability in the ice/water boundary layer, and is influenced by the relative velocity between ice and water, amount of heat available in the water, ice roughness and internal waves, etc. So in many situations the purpose of studying the eddy-correlate method is to determine the heat transfer coefficient of the bulk formula (Omstedt and Svensson, 1992; Shirasawa and Ingram, 1997) for the bulk method can be used to calculate the oceanic heat flux directly in sea ice numerical simulation and forecast.

The key to the oceanic heat flux calculation with bulk formula is to determine heat transfer coefficient. In the past, a series of values of heat transfer coefficient C_h have been determined. For example, Josberger(1987) found that C_h was in the range of $2\sim8\times10^{-4}$ according to the test results in the Bering Sea and the Fram Strait. In the Resolute Passage Sea of Canada, as measured by

Shirasawa *et al.* (1997), C_h was near 2.3×10^{-3}. In the East Arctic, Omested *et al.* (1992) obtained $C_h=(2.8\pm1)\times10^{-3}$. The prime reason for the difference of C_h above was that the heat transfer coefficient has close relation with water salinity, ice type, ice thickness, and other factors.

In the present study, we focus mainly on the measurements taken on the JZ20-2 platform in the north Bohai Sea. The meteorological and oceanographic data, and ice conditions were measured in the winter of 1997/1998. The heat transfer coefficient and the oceanic heat flux are calculated, and their influence factors are discussed.

1 Mathematical Formulation of Heat Transfer Coefficient

In the previous study of oceanic heat flux, several different bulk formulas were adopted. In the widestly applied method, considering ice-water relative velocity, water density, and specific heat of water, the oceanic heat flux can be calculated as(Omstedt, 1992; Shirasawa and Ingram, 1997; Josberger, 1987)

$$F_w = \rho_w c_p C_h u_{wi}(T_w - T_m) \tag{1}$$

where F_w is the oceanic heat flux, ρ_w is the water density, C_h is the heat transfer coefficient, T_w is the water temperature, and T_m is the temperature at the ice/water interface.

To calculate the heat transfer coefficient in the equation (1), the oceanic heat flux should be determined firstly. In the residual method, the ocean heat flux is calculated as the difference between vertical heat flux within the growing sea ice and the latent heat released by freezing at the ice-water interface. As the ice of Bohai Sea is not thick enough, the solar radiation at sea ice bottom should be considered. At any location in the growing ice sheet, the energy balance at the ice-water interface can be described by

$$F_w = -\rho_i L_i\left(\frac{dh_i}{dt}\right)_0 - F_c - Q_{sb} \tag{2}$$

where ρ_i is the sea ice density, L_i is the heat of fusion of sea ice, $\left(\frac{dh_i}{dt}\right)_0$ is the sea ice growth rate at the ice-water interface, F_c is the heat conduction, and Q_{sb} is the solar radiation at the sea ice bottom. When ice thickness $h_i > 0.5m$, Q_{sb} can be ignored, but in the Bohai Sea, the ice is very thin (usually $h_i < 0.2m$), the sea ice growing rate is affected by the solar radiation.

The simultaneous equation of equations (1) and (2) can be written as

$$\rho_w c_p C_h u_{wi}(T_w - T_m) = -\rho_i L_i\left(\frac{dh_i}{dt}\right)_0 - (F_c + Q_{sb}) \tag{3}$$

Regarding the value of C_h as a constant from time t_1 to time t_2, and integrating the equation (3), we can obtain

$$C_h = \frac{-\rho_i L_i \Delta h - \int_{t_1}^{t_2}(F_c + Q_{sb})dt}{\int_{t_1}^{t_2}\rho_w c_p u_{wi}(T_w - T_m)dt} \tag{4}$$

where, Δh is the ice thickness change from time t_1 to time t_2, u_{wi}, T_w, T_m, F_c and Q_{sb} are

are all the variables of t.

2 Calculation of Heat Transfer Coefficient in the Bohai Sea

To study the characters of sea ice growth, drifting and breakup, a field sea ice observation station is established on the JZ20-2 oil/gas platform in the Liaodong Bay. The meteorological data, oceanographic data and sea ice parameters can be measured in the winter. Moreover, the solar radiation, conductive heat flux and relative water velocity at the ice cover bottom can be calculated with a sea ice dynamic-thermodynamic model. With the data measured and calculated, the heat transfer coefficient can be determined with the equation (4).

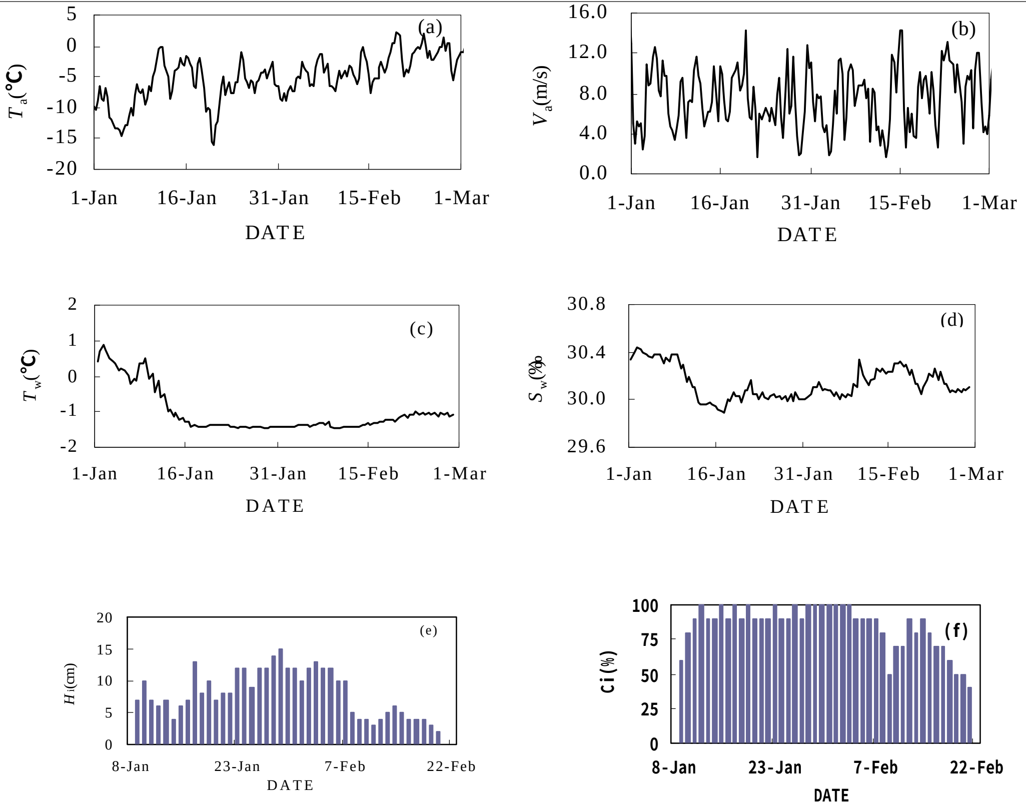
2.1 Instrumentation on the JZ20-2 platform

The sea ice observation system on the JZ20-2 platform mainly consists of four subsystems, i.e. weather station, current meter, marine radar system and video recorders. With the weather station, air temperature, wind velocity, relative humidity, atmospheric pressure and solar radiation are recorded continuously. With the current meter, water temperature, salinity, current velocity and tidal level are recorded per 15-minute during the whole ice season. A video camera run by a computer automatically is fixed on a platform pile. When the ice cover is broken and turned up under the action of ice-broken cone, the sea ice thickness is measured with the video camera. At the same time, the sea ice type and velocity are also measured. Through the marine radar system, ice velocity, ice type can be observed. In the winter of 1997/1998, the ice season for the JZ20-2 area was about 40 days, from 8 January to 20 February 1998. In the whole ice season, air temperature, wind velocity, water temperature, water salinity, ice thickness and compactness measured with the sea ice observation system are shown in Fig. 1.

2.2 Calculation of heat transfer coefficient

In the Bohai Sea, the sea ice breaks up constantly under the action of wind, current and tide, so the growth of the ice thickness is discontinuous, which will bring some trouble to the sea ice numerical simulation with a dynamic-thermodynamic model. In order to deal with the problem, the whole ice period is divided into several periods, and each one is about 3−5days, in which the influence of dynamic action is not strong, and the simulated sea ice thickness may be modified with the observed data.

With the ice thickness measured at 8:00 and 17:00 in three days from1998−01−11 to 1998−01−14, the solar radiation and the conductive heat flux at the ice-water interface, the relative velocity and temperature between ice bottom and water were calculated with the sea ice numerical model from 00:00 of 1998−01−11 to 00:00 of 1998−01−14, and the results are shown in Fig. 4. With the equation (4), some results in the calculation process are listed in Table 1, and the mean value of the heat transfer coefficient in the three days is 0.26×10^{-3}.



Fg. 1 Time series plots of (a) air temperature, (b)wind velocity, (c) water temperature, (d) current velocity, (e) ice thickness, (f) ice compactness measured in the JZ20-2 area in the 1997/1998 winter.

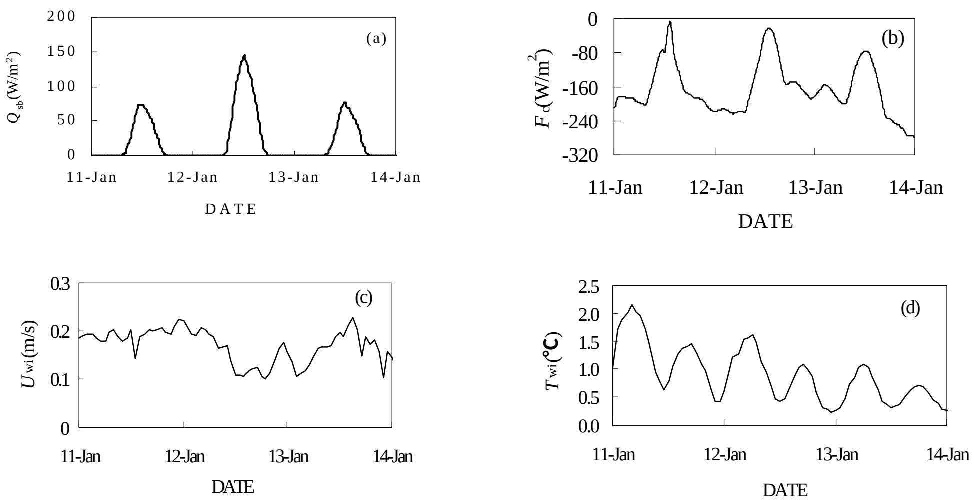


Fig. 2 Sea ice thermodynamic and dynamic factors calculated from 00:00 of 1998-01-11 to and 00:00 of 1998-01-14.

(a) solar radiation at the ice-water interface (Q_{sb}), (b) conductive heat flux at the ice-water interface (F_c), (c) relative velocity between the ice and water (U_{wi}), (d) temperature difference (T_{wi}).

Tab. 1 Some results in the calculation process for the heat transfer coefficient

DATE	TIME	h_i (cm)	Δh_i (cm)	$\int_{t_1}^{t_2} u_{wi}(T_w - T_m)dt$ ($\times 10^3 J \cdot m^{-2}$)	$\int_{t_1}^{t_2}(Q_{sb} + F_c)dt$ ($\times 10^6 J \cdot m^{-2}$)	C_h ($\times 10^{-3}$)
1998-01-11	08:00	7.0	--	--	--	--
	17:00	6.0	--1.0	5.92	--2.17	0.21
1998-01-12	08:00	8.0	2.0	6.01	--11.11	0.19
	17:00	6.5	--1.5	3.25	--0.27	0.35
1998-01-13	08:00	8.0	1.5	4.77	--9.21	0.23
	17:00	7.0	--1.0	3.99	--2.66	0.34

With the method above, the heat transfer coefficient in the winter of 1997/1998 is calculated, and the results are shown in Fig.3. In the freezing and melting periods, the heat transfer coefficient has smaller values, which were 0.16×10^{-3} and 0.04×10^{-3} respectively. In the middle of the ice season , it is up to 0.5×10^{-3}. On the basis of heat transfer coefficient determined above, the oceanic heat flux in the whole winter of 1997/1998 is calculated with bulk formula, and the results are shown in Fig. 4. The results show that the oceanic heat flux is different in the whole winter. In the freezing period, the oceanic heat flux is more than $300W/m^2$, and then decreases continuously with the extension of the ice season. At the end of the ice season, it trends to zero.

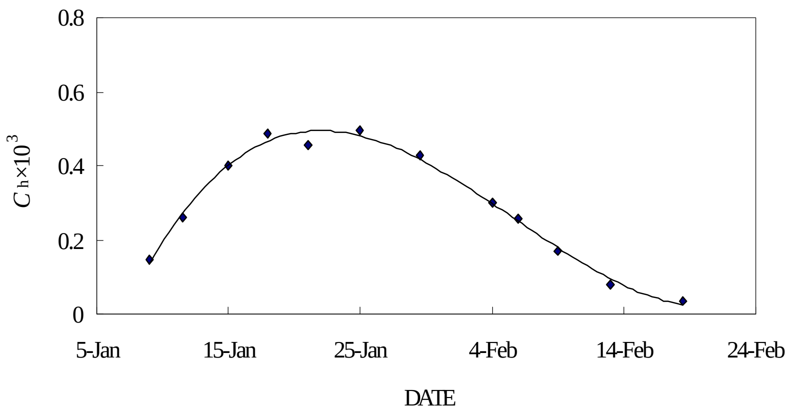


Fig. 3 Heat transfer coefficient (C_h) and its fitting curve in the winter of 1997/1998

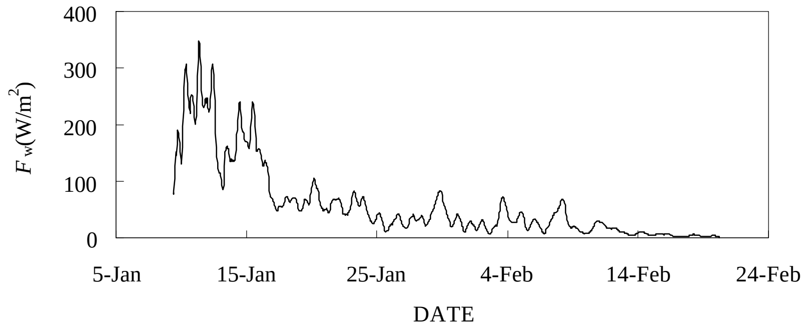


Fig. 4 Oceanic heat flux (F_w) calculated with the heat transfer coefficient in the winter of 1997/1998

3 Discussion

The heat transfer coefficient controls the value of oceanic heat flux directly, and also has great influence on the results of sea ice numerical simulation and prediction. The bulk method of oceanic heat flux is a semiempirical formula, in which the heat transfer coefficient is usually set as a constant value. In fact, the heat transfer coefficient is sensitive to ice thickness and ice roughness. From the results above, it is shown that the value of heat transfer coefficient has a smaller value in the freezing and melting periods, and in the middle ice season, it has a large value. The influences of ice thickness and ice type on the heat transfer coefficient are described as follows.

(1) Ice thickness. Under the condition of thin ice cover, the water exchanges heat with the atmosphere through ice cover easily. At the bottom of thick ice cover, the temperature gradient is lower than that of thin ice cover, which affects the heat exchange between ice cover and water. From the change of ice thickness and heat transfer coefficient of the winter of 1997/1998, we can find that the heat transfer coefficient increases with ice thickness.

(2) Ice type. The roughness of level ice, rafted ice and pancake ice is different obviously. Based on the boundary theory of ice cover, the contact area of ice and water increases with ice roughness, which causes the heat transfer sufficiently. Therefore, the heat transfer coefficient of rough ice is larger than that of smooth ice.

4 Conclusions

The heat transfer coefficient is calculated based on the sea ice dynamic-thermodynamic numerical simulation, and the meteorological data, oceaographic data and sea ice conditions measured on the JZ20-2 oil/gas platform in the Bohai Sea in the winter of 1997/1998. The results show that the heat transfer coefficient is different at different times. It is smaller in the freezing and melting periods, which is 0.16 0^{-3} and 0.04×10^{-3} respectively. In the middle of the ice season, the heat transfer coefficient has a lager value, which is about 0.5×10^{-3}. According to the heat transfer coefficient calculated in this paper, the oceanic heat flux in the winter of 1997/1998 is calculated. It is more than 300 W/m^2 in the initial ice period, and then decreases with the ice period. At the end of the ice period, it is close to zero. Based on the sea ice data measured on the JZ20-2 platform and the heat transfer coefficient determined above, it is found that the heat transfer coefficient has close relationship with roughness and thickness of ice cover.

In the JZ20-2 sea area of the Liaodong Bay, the heat transfer coefficient has been calculated and has passed the reliability check, but its accuracy should be examined in other areas of the Bohai Sea. With further study, the oceanic heat flux of the whole Bohai Sea can be calculated with bulk formula to improve the computational precision of sea ice numerical simulation and prediction.

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References

[1] Harvey L D D. (1990) Testing alternative parameterizations of lateral melting and upward basal heat flux in a thermodynamic sea ice model. *Journal of Geophysical Research*, **95** (C5): 7359-7365.

[2] Josberger E G. (1987) Bottom ablation and heat transfer coefficients from the 1983 Marginal Ice Zone Experiment. *Journal of Geophysical Research*, **92** (C7): 7012-7016.

[3] Lu Qian-Ming (1987) On Mesoscale Modeling of the Dynamics and Thermodynamics of Sea Ice, Technical University of Denmark.

[4] Lytle V I and Ackley S F. (1996) Heat flux through sea ice in the western Weddell Sea: Convective and conductive transfer processes. *Journal of Geophysical Research*, **101** (C4): 8853-8868.

[5] Maykut G A. (1986) The surface heat and mass balance. In: N. Untersteiner (Editor), *The Geophysics of Sea Ice.* Plenum New York, NY, 395-465.

[6] Mcphee M G, Maykut G A and Morison J H. (1987) Dynamics and thermodynamics of the ice/upper ocean system in the marginal ice zone of the Greenland Sea. *Journal of Geophysical Research*, **92** (C7): 7017-7031

[7] Moore R M and Wallace D W R. (1988) A relationship between heat transfer to sea ice and temperature-salinity properties of Arctic ocean waters. *Journal of Geophysical Research*, **93** (C1): 565-571.

[8] Omestedt A and Svensson U. (1992) On the melt rate of drifting ice heated from below. Cold Regions Science and Technology, 21: 91-100.

[9] Omstedt A and Wettlaufer J S. (1992) Ice growth and oceanic heat flux: Models and Measurements. *Journal of Geophysical Research*, **97** (C6): 9383-9390.

[10] Parkinson C L and ishington W M. (1979) A large-scale numerical model of sea ice. *Journal of Geophysical Research*, 84: 311-337.

[11] Shirasawa K and Ingram G R. (1997) Currents and turbulent fluxes under the first-year sea ice in Resolute Passage, Northwest Territories, Canada Journal of Marine System, 11:21-32.

[12] Shirasawa K, Ingram G R and Hudier E J J. (1997) Oceanic heat flux under thin sea ice in Saroma-ko Lagoon, Hokkaido, Japan. Journal of Marine System, 11:9-19.

[13]Tang C L. (1991) A two-dimensional thermodynamic model for sea ice advance and retreat in the Newfoundland Marginal Ice Zone. *Journal of Geophysical Research*, **96** (C3): 4723-4737.

[14] Wang Renshu. (1984) Numerical tests of Bohai Sea ice. *Acta Oceanologica Sinica*(in Chnese), **6** (4): 572-580

[15] Wettlaufer J S. (1991) Heat flux at the ice-ocean interface. *Journal of Geophysical Research*, **96** (C4): 7215-7236.