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Experimental investigation on the influence of heaving and yawing on the heat transfer coefficient and pressure drop of the plate evaporator

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Abstract

Plate heat exchangers are widely used in energy systems. The offshore floating platform's ocean thermal energy conversion (OTEC) system will be affected by the sea surface's wind, waves, tides, and currents, resulting in various motion postures. The additional inertia force brought by different motion postures will change the heat transfer characteristics of the heat exchanger, among which yawing and heaving are representative. Therefore, this paper carries out an experimental study on the influence of yawing and heaving format on the heat transfer coefficient and pressure drop of a herringbone corrugated plate evaporator using a heat exchanger thermal performance testing system and a six-degree-of-freedom platform. The experimental results show that both yawing and heaving formats have enhanced effects on the heat exchange coefficient of the herringbone corrugated plate evaporator, and it is more evident in the heaving format. The total heat transfer coefficients of the heat exchangers under different swaying motion conditions are significantly improved compared with the land-based state, and the enhanced heat transfer ranges from 7.03% to 20.61%. The plate evaporator has sound resistance effects on the pressure drop of the evaporator in both yawing and heaving formats. The "herringbone" corrugated plate evaporator has good resistance to the pressure drop of the evaporator for both bow yawing and heaving format, and the pressure drop has no noticeable change compared with the stable working conditions in these two motions.

***Key words* :** OTEC, plate heat exchanger, yawing and heaving format, pressure drop, heat transfer.

Nomenclature

Φ	quantity of heat(W)
k	Heat transfer coefficient of microcell area(W/(m^2·°C))
Δt	Temperature difference of heat transfer between fluids(°C)
dA	Microunit heat transfer area
K	Average heat transfer coefficient(W/(m^2·°C)
Δt_m	The log-mean temperature difference between fluids(°C)
Q_R	The heat absorbed by the refrigerant(W)
M_R	Mass flow of refrigerant(kg/s)
Δh_R	Enthalpy difference between refrigerant import and export(J/kg)
Q_L	Heat release on the hot water side(W)
G_L	volume flow of hot water(m^3/s)

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ρ_L	entity of hot water(kg/m^3)
c_{pL}	The specific heat capacity of hot water at constant pressure(J/(kg·K))
$m_{w,ts}$	Hot water side mass flow rate
$T_{w,ts,in}$	Inlet temperature of hot water(°C)
$T_{w,ts,out}$	outlet temperature of hot water(°C)
T_e	Evaporation temperature(°C)
ΔQ	thermal balance error(%)
h	total heat transfer coefficient(°C)
h_{ref}	heart side heat transfer coefficient
a	yawing amplitude(°)
β	heaving amplitude(mm)

1. Introduction

In recent years, the development and utilization of marine resources has become an essential strategy for national economic development (Zhang C B,2023), and ocean thermal energy conversion has received widespread attention as a marine renewable energy source. Ocean thermal energy conversion is the primary way to utilize ocean temperature difference energy (Weimin Liu,2020). The ocean thermal energy conversion involves a variety of thermal cycles, including the organic Rankine cycle, the Kalina cycle, the Uehara cycle, etc. (Fan C C,2023) . In these thermal cycles, the heat exchanger is one of the critical thermal energy conversion components, and the herringbone corrugated plate heat exchanger has the advantages of a high heat transfer coefficient, compact structure, and slight temperature difference at the end, which is a standard heat exchanger element in the OTEC system. (Ji Zhang,2019 and Hu Z,2022)

The ocean thermal energy conversion set up on the floating platform at sea will be affected by the wind, waves, tides, and currents on the sea surface and generate a variety of motion format (Zhen Tian,2020). The additional inertia force brought by different motions will change the two-phase flow heat transfer characteristics inside the heat exchanger (Chen Chong,2015), which in turn affects the dynamic state of the system and threatens its safe and stable operation. Among all the ocean motion format, yawing and heaving are the two motion format that account for a large proportion. Among them, yawing refers to the rotational motion of the ship's front part (bow) relative to the horizontal plane, and heaving format refers to the periodic vibration motion of the ship in the vertical direction in the water. These two format may impact the performance of plate heat exchangers in ocean thermal energy conversion systems (Jinghua Wei,2011). The reason may be that the ocean motion causes the medium on both sides of the plate to form a complex flow pattern on the corrugated plate, resulting in the irregular passage of the fluid through the corrugated plate, which affects the heat transfer and heat exchange efficiency. At present, the experimental studies on the thermal performance of heat exchangers under ocean motion conditions have focused more on casing or shell and tube heat exchangers under tilting and swaying formats, without involving the herringbone-shaped corrugated plates, and also lacked the rule of change of the influence of yawing and heaving motion on the thermal performance of heat exchangers.

Based on the current research situation, this research simulates two kinds of motion postures of yawing and heaving by using a six-degree-of-freedom platform through the heat exchanger thermal performance testing system with R410A as the working fluids and experimentally researches the heat transfer characteristics of the herringbone corrugated plate evaporator with different flow rates of the working fluids, yawing and heaving postures under different motion frequencies; and probes the change rules of the two postures on the influence of the heat transfer characteristics. The change rule of the influence of the two formation the heat transfer characteristics is investigated

2. Method and theoretical analysis

2.1 Test setup and six-degree-of-freedom platform

To realize the determination of the heat transfer coefficient and pressure drop of the herringbone corrugated plate evaporator, a test system was designed and constructed, which consists of an R410A process circuit, a cold water circuit, and a hot water circuit, as shown in Fig. 1.

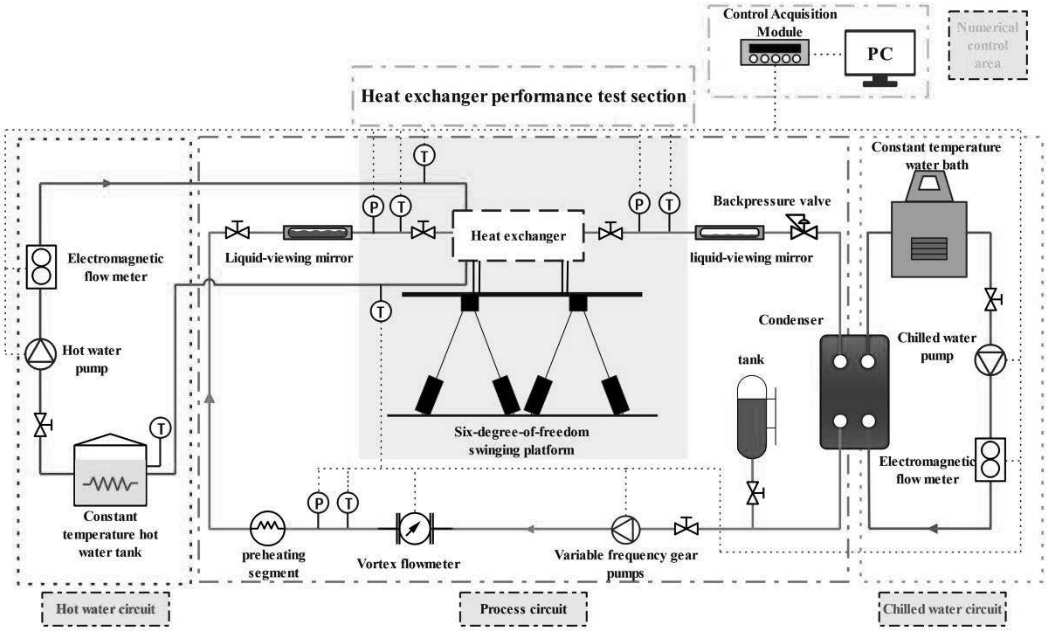

Figure 1(a) Heat exchanger thermal performance testing system

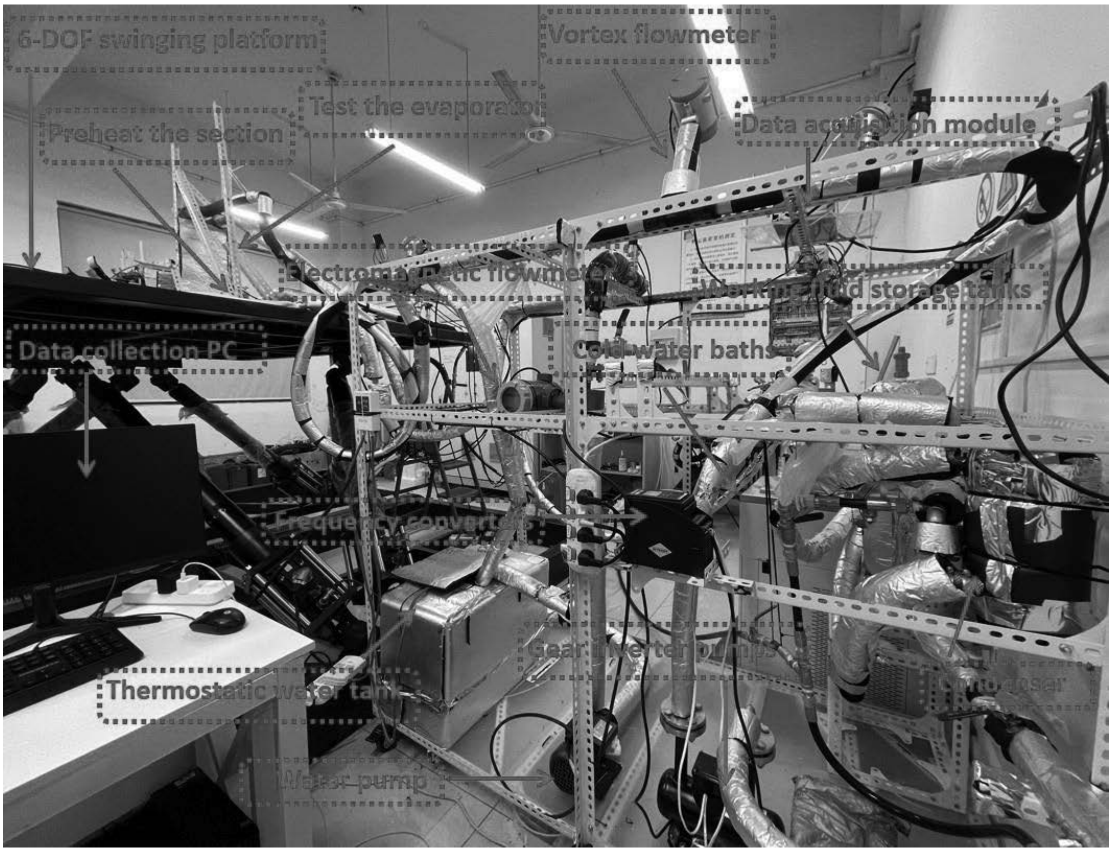

Fig. 1 (b) Six-degree-of-freedom platform

The working fluid circuit consists of a tank, a plate heat exchanger, two coil heat exchangers, a centrifugal pump, an electric heater, and a test section. Fluid from the tank through the centrifugal pump into the preheating area, through the electric heater to ensure that the liquid is no longer in a supercooled state and saturated state, and then the watery form of the mass into the test section, and then the mass of the fluid in the test section of the evaporator is heated to the superheated state, and then flow into the condenser and the supercooled by which the cold fluid condensation to the supercooled state, and finally flow back to the storage tank. Finally, it flows back to the storage tank. The 6-DOF (Six Degrees of Freedom) motion platform can generate periodic single-degree-of-freedom motions or multiple-degree-of-freedom coupled motions, and the test section is connected by a high-pressure oil pipe to avoid the possibility of damage to the pipeline during the motion and to prevent leakage of the work material.

2.2 Test section

To reflect the actual heat transfer performance of the "herringbone" corrugated plate heat exchanger under ocean movement conditions, the plate heat exchanger in this test uses the vacuum brazing method, and the material is 304 stainless steel. The structural parameters are determined according to the requirements of the heat exchanger in the actual ocean temperature difference power generation system.

The test section can be divided into mass, thermal fluid, and measurement. Work part to ensure that R410A saturated liquid state into the heat exchanger, saturated gas state or superheated gas state out of the heat exchanger to avoid uneven distribution of the two phases of the measurement error will be caused by the same time to ensure that the temperature of R410A into the heat exchanger to reach the test preset temperature. The thermal fluid part needs to ensure that the thermal fluid entering the heat exchanger during the test remains at the preset temperature of the test.

In the measurement part, the inlet and outlet of the work material and the inlet and outlet of the plate heat exchanger thermal fluid are selected as the measurement points. The temperature and pressure of the inlet and outlet of the working fluid side and the hot water measurement are measured by PT100 RTD and diffusion silicon manometer. During installation, liquid raw tape ensures the test system is sealed to prevent leakage. At the same time, all PT100 RTDs in the system are calibrated by a high-precision rhodium-iron resistance thermometer before use, and the uncertainty of the calibrated PT100 RTDs is within ±0.1°C. The instrument can directly measure the working fluid's temperature, pressure, and volume flow rate. The working fluid's mass flow rate can be calculated by utilizing the fluid properties in the NIST REFPROP database. The heat exchange capacity on the hot liquid side can be calculated from the corresponding inlet and outlet temperatures of the hot liquid side, and the calculation of the heat exchange capacity of the hot fluid and the inlet and outlet temperatures of the working fluid side can obtain the heat transfer coefficient of the plate heat exchanger. Plate heat exchanger pressure drop can be obtained from the difference between the corresponding pressures of the import and export of the working fluid side.

2.3 Test conditions

To quantitatively analyze the heat transfer performance of the herringbone corrugated plate heat exchanger under ocean motion conditions, the test operating conditions of the plate heat exchanger were set up to simulate the ocean motion conditions, including the temperature, pressure, and volume flow rate of the thermal fluid side. R410A is selected as the work material according to the operation process and operation conditions in the ocean temperature difference power generation. With low ozone depletion potential and high refrigeration performance, it is widely used in various industrial and commercial refrigeration equipment. R410A's density is usually between 1.2~1.5 g/cm³ under standard temperature and pressure conditions. Its specific heat capacity is about 0.59~0.65 kJ/(kg-K). Its latent heat of evaporation is about 260~280 kJ/kg.

2.4 Theoretical calculation of evaporative heat transfer coefficient

The theoretical basis for heat exchanger thermal measurements is the principle of thermal equilibrium: thermal equilibrium between hot and cold fluids, i.e., the amount of heat absorbed and emitted.

The general form of the heat transfer equation:

$$\Phi = \int_0^F k\,\Delta t dA$$

Φ —heat,W ;

k—$heat$ transfer coefficient of any microcell area of the heat exchanger, W/(m²·°C)

Δt—Temperature difference between the two fluids in this microcell area,℃

dA—Micro-unit heat transfer area;

The following simplified heat transfer equation is usually used in practical engineering:

$$\Phi = KA\Delta t_m$$

Φ—-heat exchange,W;

K—Average heat transfer coefficient over the entire heat exchanger area,W/(m²·°C)

Δt_m—logarithmic mean temperature difference between the two fluids,℃

The following describes the calculation formula corresponding to the measured thermal performance of the plate heat exchanger.

Heat absorption on the refrigerant side:

$$Q_R = M_R \Delta h_R$$

Q_R—Heat absorbed by the refrigerant,W;

M_R—Mass flow rate of refrigerant,kg/s;

Δh_R—Enthalpy difference between refrigerant inlet and outlet,J/kg;

Water-side heat release:

$$Q_L = G_L \rho_L c_{pL} \left(T_{w,ts,in} - T_{w,ts,out}\right)$$

Q_L—heat release on the hot water side,W;

G_L—Volume flow rate of hot water,m^3/s;

ρ_L—Density of hot water,kg/m^3;

c_{pL}—-Specific heat capacity of hot water at constant pressure,J/(kg·K);

$T_{w,ts,in}$—Hot water inlet temperature,℃;

$T_{w,ts,out}$—Hot water outlet temperature,℃;

Relative error of heat balance:

$$\Delta Q = \frac{(Q_R - Q_L)}{Q_L} \times 100\%$$

ΔQ—-Thermal balance error,%;

$Refrigerant$ heat absorption,W;

Q_L—heat release on the hot water side,W;

Log mean temperature difference:

$$\Delta t_m = \frac{\left(T_e - T_{w,ts,out}\right) - \left(T_e - T_{w,ts,out}\right)}{\ln \frac{T_e - T_{w,ts,out}}{T_e - T_{w,ts,out}}}$$

Δt_m—log mean temperature difference,℃;

T_e—Evaporating temperature,℃;

$T_{w,ts,in}$—Hot water inlet temperature,℃;

$T_{w,ts,out}$—Hot water outlet temperature,℃;

The temperature difference in the plate heat exchanger is calculated using the logarithmic heat transfer temperature differenceΔt_m. As in the above equation because the heat transfer curve on the water side of the plate heat exchanger is not linear. So, the logarithmic heat transfer temperature difference is an integral mean

Total heat transfer coefficient:

$$h = \frac{Q_L}{(A \Delta t_m)}$$

h—Total heat transfer coefficient, W/(m2·℃);

Q_L—heat release on the hot water side, W;

A—Heat exchange area,m^2;

Δt_m—blogmeantemperature difference,℃;

3 Uncertainty analysis

The direct errors generated by all the instrumentation used in this test are listed in Table 1.

Table 1 The direct errors generated by all the instrumentation

Instrument uncertainty	Typology	Measurement range	Uncertainties

instrument			
temperature sensor	PT100	-50~150℃	2%
Pressure sensors	Diffusion Silicon Manometer	0~2500kPa	0.6%
flowmeter	Electromagnetic flow meter	$0\sim5m^3/h$	0.5%
	Vortex Flow Meter	$0\sim5m^3/h$	1.3%

At the same time, in a complex test system, the indirect error is affected by the theory on which it is based, the number of instruments used, the length of time experienced, etc., and each increment in the process will increase the chance of introducing error. This test system's analysis of indirect mistakes is based on the error transfer theory. The main indirect error of this test occurs in the two parts of the test section: water-side heat transfer error and heat transfer coefficient error. The following formula can be calculated; the results are listed in Table 2.

Water-side heat transfer error in the test section:

$$\xi(Q_L) = \sqrt{\frac{\xi_{m_{w,ts}^2}}{m_{w,ts}^2} + 2\frac{\xi_{PT}^2}{(T_{w,ts,in} - T_{w,ts,out})^2}}$$

Predicted uncertainty of the water-side heat transfer coefficient: For the expected fate of the water-side heat transfer coefficient, it can generally be considered to be within +10%. Let $\alpha = T_e - T_{w,s,in}$, $\beta = T_e - T_{w,t,out}$, $\varepsilon_\alpha = \sqrt{2 \times \xi_{PT}^2}$, $\varepsilon_\beta = \sqrt{2 \times \xi_{PT}^2}$。

$$\xi(\Delta t_m) = \sqrt{\varepsilon_\alpha^2 + \varepsilon_\beta^2 + \left(\frac{\varepsilon_\alpha}{\alpha}\right)^2 + \left(\frac{\varepsilon_\beta}{\beta}\right)^2}$$

Total heat transfer coefficient error for the test section.

$$\xi(h) = \sqrt{\xi_{\Delta t_m}^2 + 2\xi_{PT}^2}$$

Refrigerant side heat transfer coefficient error.

$$\xi(h_{ref}) = \sqrt{\xi_{\Delta t_m}^2 + \xi_h^2}$$

Table 2 The main indirect error of this test

Test Uncertainty Indirect Measurement Parameters	Uncertainty
Water-side heat transfer in the test section. Q_L	$\pm3.6\%$
Log-mean temperature difference. Δt_m	$\pm4\%$
Total heat transfer coefficient of the test section, h	$\pm4.8\%$
Refrigerant side heat transfer coefficient. h_{ref}	$\pm6.2\%$

4 Results and discussion

4.1 Influence of yawing format on heat transfer coefficient

Comparison of heat transfer coefficients under the conditions of constant mass flux of thermal fluid of 175 kg/(m^2·s), constant temperature of 25℃, mass flux of R410A on the mass side of the vessel of

125-225 kg/(m²·s), temperature of 10℃, yawing amplitude of 2.5°-7.5°, and yawing frequency of 0-1Hz is shown in Fig. 2. Under different yawing conditions, the total heat transfer coefficient of the heat exchanger shows an overall trend of enhancement compared with the land-based state, and the enhancement is up to 10.24%. Under different yawing amplitudes, the change rule of frequency on the heat transfer coefficient tends to be the same; the enhanced heat transfer effect is significant at lower frequencies and weakens at higher frequencies. Meanwhile, the influence of different yawing amplitude on the heat transfer coefficient also shows a regular change; the peak value of the heat transfer coefficient occurs at 0.4Hz when the yawing amplitude is 2.5°, and the peak value of the heat transfer coefficient occurs at 0.2 Hz when the yawing amplitude is 5° and 7.5°. Thus, it can be judged that the heat exchanger's total heat transfer coefficient has an overall enhancement trend compared with the land-based condition. The enhancement is the largest at 10.24%. The peak value of the heat transfer coefficient occurs at 0.2 Hz for 5° and 7.5° of the yawing amplitude. Thus, it can be judged that the optimal frequency of enhanced heat transfer under yawing motion becomes lower with the increase in amplitude and is generally distributed in the low-frequency band. Compared with the land-based condition where the mass flows and boils in a stable film between the plates, the yawing format adds the effect of rotating centrifugal force to the flow of the group between the leaves, which disturbs the original stable flow of the mass between the plates, speeds up the process of breaking up the liquid film, and then strengthens the effect of heat transfer with the hot fluid; meanwhile, under the condition, the impact of the movement frequency and amplitude of movement on the enhancement of heat transfer coefficient is similar, and there is no noticeable difference. There is no significant change under the same volume flow rate for the pressure drop of the "herringbone" corrugated plate heat exchanger under yawing motion as shown in Fig.3.

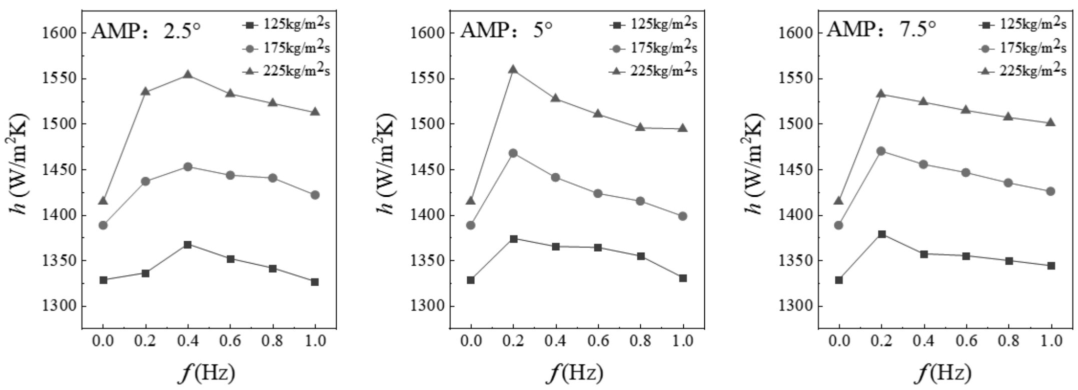

Fig. 2 Total heat transfer coefficients of heat exchangers with different frequencies in yawing format

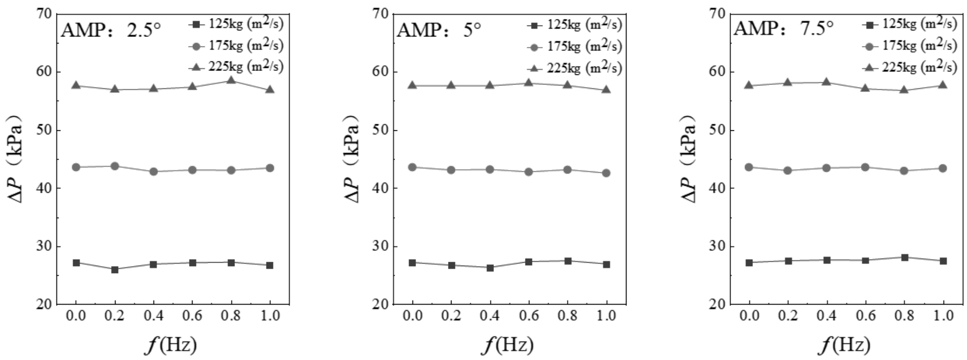

Fig.3 Pressure drop of work material with different frequencies in yawing format

4.2 Effect of heaving format on heat transfer coefficient

The comparison of heat transfer coefficients under the conditions of constant thermal fluid mass flux of

175 kg/(m2·s), constant temperature of 25°C, mass flux of R410A of the vessel of 125-225 kg/(m2·s), temperature of 10°C, heaving amplitude of 50 mm to 100 mm, and heaving frequency of 0.2-1 Hz are shown in Fig.4. The total heat transfer coefficients of the heat exchangers under different heaving motion conditions are significantly improved compared with the land-based state, and the enhanced heat transfer ranges from 7.03% to 20.61%. Compared with the heat transfer coefficient in the heaving motion format, the heat transfer coefficient under the same mass flow rate can be increased up to 13.66% as shown in Fig.4. In the heaving format, the heat transfer coefficient increases with the increase of heaving amplitude, and the effect of frequency on the heat transfer coefficient is similar to that of the yawing motion condition, with significant enhancement of heat transfer effect at a lower frequency and weakening of enhancement of heat transfer effect at a higher frequency. Compared with the land-based state in which the work material is boiling in a stable membrane flow between the plates, the heaving format adds a bias force to the flow of the work material between the leaves, which disturbs the original steady flow of the work material between the plates, accelerates the process of liquid film breakup, and then strengthens the effect of heat transfer with the hot fluid; the pressure drop of the herringbone plate heat exchanger in this format is the same as that in the yawing motion format as shown in Fig.5.

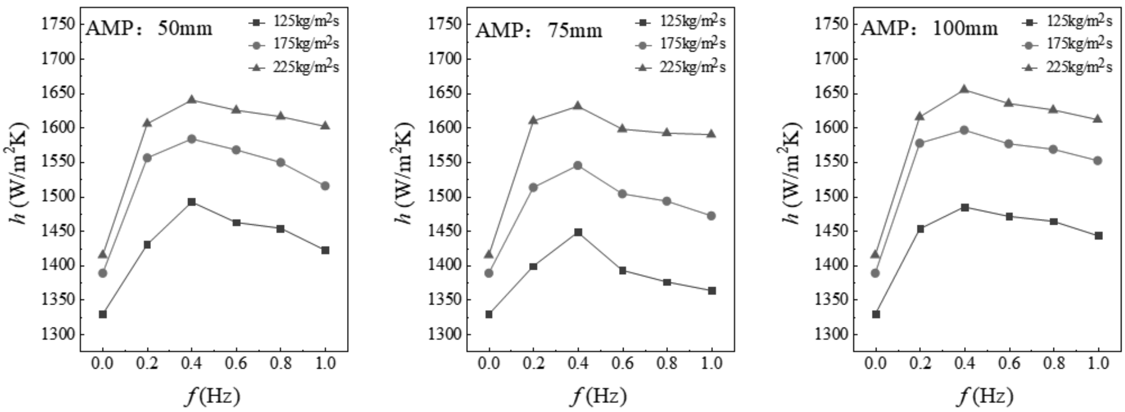

Fig.4. Total heat transfer coefficient of the heat exchanger at different frequencies in heaving format

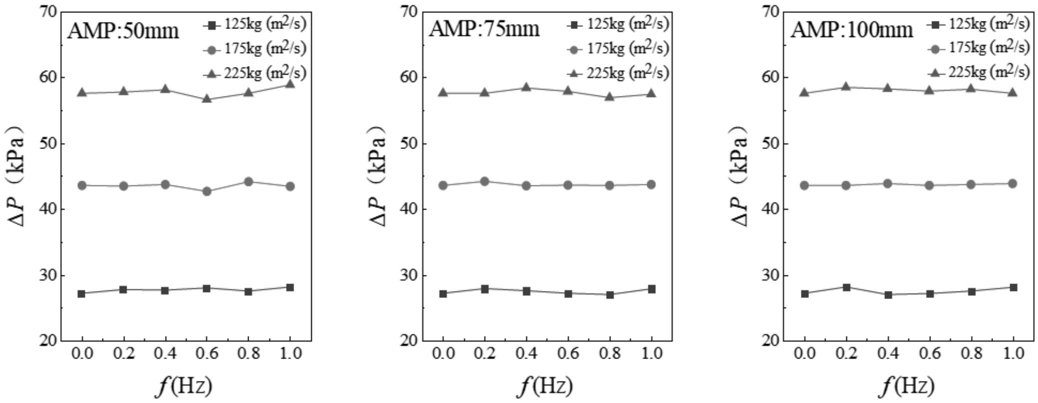

Fig.5. Pressure drop of working fluid at different frequencies in heaving format

Yawing and heaving format in this test have enhanced heat transfer effects on the "herringbone" corrugated plate heat exchanger. There is no significant difference between the effect of motion frequency and motion amplitude on the heat transfer coefficient in yawing motion. In contrast, the effect of motion amplitude on the heat exchanger's enhanced heat transfer is significantly higher than that of motion frequency on the heat exchanger in heaving format. The reason may be as follows. The reason may lie in compared with the land-based condition where the working fluid is boiling in a stable membrane flow between the plates, the addition of a specific motion format disrupts the stable flow of the work material between the plates, and then the process of boiling into a film is destroyed, the liquid film is broken under the action of the additional inertial force brought about by the motion, which strengthens the effect of heat transfer with the hot fluid; and the different motion format play a different role in the influence of the process, and therefore, bring different strengthening effects. The different motion postures have different effects on this process, bringing different intensification effects. In this experiment, the two degrees of freedom motions have no significant effect on the pressure drop of the herringbone corrugated plate heat exchanger

5 Conclusion

In this paper, a thermal performance test platform for heat and mass exchange equipment under oceanic motion conditions is designed and constructed, and the thermal performance of the herringbone corrugated plate evaporator is tested under the yawing and heaving with R410A as the working fluid and herringbone corrugated plate evaporator as the research object, and the following conclusions are drawn:
(1) Both yawing and heaving motions reinforce the heat transfer coefficient of the herringbone corrugated plate evaporator, which is more evident in the heaving motion.
(2) The herringbone corrugated plate evaporator has excellent resistance to the pressure drop of the evaporator for both yawing and heaving formats, and there is no significant change in the pressure drop in these two format compared with the stable condition.
(3) In this paper, only the thermal performance of the herringbone corrugated plate evaporator under the two format of yawing and heaving has been experimentally investigated. The thermal performance characteristics of herringbone corrugated plate evaporator under other motion conditions will be explored in the future.

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