KSME Journal, Vol. 9, No. 1, pp. 19~28, 1995

Liquid-Liquid Direct Contact Heat Exchanger for Solar Application

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(Received February 3, 1994)

In most direct contact liquid-liquid heat exchangers, oil or hydrocarbon with a density less than water is normally used as dispersed working fluid. The main difficulty that arises with this arrangement lies in the control of the interface at the top of the column. When it is closely connected with a solar collector which uses water as its working fluid, the main difficulties arise from the fact that the water can be frozen during winter time. In order to solve these problems and to demonstrate the technical feasibility of a direct contact liquid-liquid heat exchanger, liquids heavier than water with low freezing temperature has been utilized as dispersed phase liquids in a small laboratory scale model made out of pyrex glass. In the present investigation, dimethyl phthalate($C_6H_4(COOCH_3)_2$) and diethyl phthalate($C_6H_4(CO_2C_2H_5)_2$) are utilized as heavy dispersed phase working fluids. The results of the present investigation support the technical feasibility in the utilization of heavier dispersed working liquid in the spray column liquid-liquid heat exchanger for a solar system. The overall average temperature difference along the column is found to be almost half of the intial temperature difference between the dispersed and the continuous phase. Despite the fact that the two phthalates tested in the experiment differ significantly in some of their physical properties, the volumetric heat transfer coefficients in terms of dispersed fluid superficial velocities were found to be similar for both phthalates tests.

Key Words : Spray Column, Direct Contact Liquid-Liquid Heat Exchanger, Solar System

Nomenclature

a : Interfacial area per unit volume, cm^{-1}
A : Area through which heat transfer occurs, cm^2
F/S : Superficial velocity of the dispersed phase liquid, cm/sec
h_c : Continuous phase (water) heat transfer coefficient, J/(sec)(cm^2)(℃)
h_d : Dispersed phase heat transfer coefficient, J/(sec)(cm^2)(℃)
k : Thermal conducitivity, (W cm)/°K
H : The fraction of the effective volume of the heat exchanger occupied by the dispersed phase (holdup), dimensionless
L : Vertical height of the continuouse phase (water) in the heat exchanger, cm
N_N : Nusselt number $= h\ d/k$, dimensionless
N_p : Prandtl number $= c\ \mu/k$, dimensionless
N_{pe} : Peclet number $= c\ \rho\ V\ d/k = N_p\ N_R$, dimensionless
N_R : Reynolds number $= d\ V\ \rho/\mu$, dimensionless
N_S : Stanton number $= \frac{U}{C_d \rho_d F/S}$, dimensionless
Q : Rate of the heat transfer, J/sec $= W$
S : Horizontal cross sectional area of the heat exchanger, cm^2
$\varDelta T_1$: Initial temperature difference, ℃
T_i : Temperature measured in the column, ℃
T_c : Temperature of the continuous phase liquid (water), ℃

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T_d : Temperature of the dispersed phase liquid, ℃
T_{co} : Temperature of the dispersed phase liquid collected at the bottom of the column, ℃
U : Overall area heat transfer coefficient, J/(sec)(cm^2)(℃)
U_V : Volumetric heat transfer coefficient, J/(sec)(cm^3)(℃) $= Ua$
V : Volume of the continuous phase in the heat exchanger, cm^3
y : Wall thickness, cm
μ_c : Viscosity of the continuous phase liquid (water), poise
μ_d : Viscosity of the dispersed phase liquid, poise

1. Introduction

For the solar energy heating system, the use of water as working fluid for the solar collector causes problem because the water can be frozen in winter time, particularly during the night. Also, it is very inconvenient to drain the water to avoid the danger of freezing the water at night. To solve this problem, ethylene glycol can be used as antifreezer with water in the solar collector. However, if the two fluids are miscible, the only way to achieve heat transfer and the separation of the liquids is the conventional tube and shell heat exchanger, which is not only expensive but also decreases the useful gain of the collector and is subject to fouling. Other disadvantages of the tube and shell heat exchanger are its physical dimensions and the high flowrate of storage tank water that has to be pumped through its tubes. The toxicity of ethylene glycol becomes another problem to the system in case of the leakage. Therefore, the direct contact mode of heat transfer has advantages over the indirect contact mode.

In addition, the temperature driving force required for the conventional heat exchanger is greatly reduced in the direct contact heat exchanger system which operates with a negligibly small temperature driving force. In most direct contact liquid-liquid heat exchangers, oil or hydrocarbon with a density less than water is normally used as the dispersed working fluid. In this case, the lighter fluid is injected into the spray column through a perforated plate at the bottom of the column. The main diffculty that arises with this arrangement lies in the control of the interface at the top of the column. The interface must remain fixed as water is introduced into the column immediately below the interface. Another problem of this type is the rate of coalescence of the drops, which influences the location of the interface at the top of the column. The rate of coalescence can be catalyzed by introduction of a honeycomb structure at the desired interface location. The main requirement is that the material is preferentially wet by the dispersed phase(Ward et al., 1977).

In order to solve the technical difficulties associated with previous designs, it is proposed to use immiscible liquids which are heavier than water insted of lighter liquids with low freezing and high boiling temperatures. By this arrangement, it becomes possible to eliminate internal parts totally from the inside of the heat exchanger column and make it effective design techanically and economically, and the problems caused by lighter working fluids are being eliminated. Therefore, the proposed system has significant advatages over conventional systems in handling low temperature sources.

In the present investigation, two working fluids, dimethyl phthalate (density : 1.130 g/cm^3 at 85℃) and diethyl phthalate (density : 1.059 g/cm^3 at 85℃), are utilized as heavier dispersed working fluids for the system. While diethyl phthalate (freezing point : -40℃, boiling point : 298℃) has no problem of freezing in winter time due to its low freezing point, dimethyl phthalate (freezing point : 0℃, boilling point : 282℃) has same problem as water because of its high freezing point. However, both fluids are considered in order to compare their thermal performances.

2. Review of Literature

The direct contact heat transfer between drops of the dispersed phase and the continuous phase is complex. It depends not only on the thermal properties of each phase, but also on the dynamics of the drops themselves. Most experiments in spray columns carried out to date have utilized drops less than 7.5 mm in diameter, more extensively drops between 1.0 mm and 3.0 mm have been utilized.

When the drops have low thermal conductivity, as is the case with hydrocarbons, it is likely that the governing resistance to heat transfer is internal to the drops. Jacobs and Golafshani(1985) investigated a model using the assumption of no drop internal resistance to heat transfer and another where the heat transfer was governed by diffusion within the drop. The latter model showed the best agreement with the temperature profile data, expecially when it accounted for drop growth.

Stamps, Barr, and Valenzuela(1986) recently developed a heat transfer model for a liquid-liquid spary column employing a one-dimensional dispersion model. Assuming the drop size and the wake volumes to be constant and the transverse temperature uniform, and assuming known heat transfer coefficients between each of three parallel streams, i.e., the upward-flowing dispersed phase drops, the wakes attached to the drops, and downward-flowing continuous phase. They were able to choose wake volume to drop volume values and heat transfer coefficients to fit known experimental temperature profiles for a variety of spray column experiments.

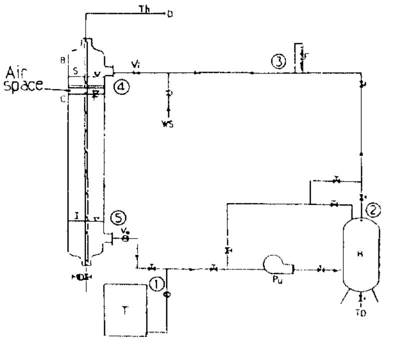
Moresco and Marschall(1980) showed that the measured overall area heat transfer coefficients were much lower than those predicted by correlations of external heat transfer coefficients for oil dispersed in water systems. It could thus be concluded that the heat transfer resistance lay mainly inside the drops.

In a liquid-liquid spray column, drops produced by a pressure distributor with identical multiple openings are never perfectly uniform. Individual drop diameters are varied by some mean, and the distribution may be narrow or broad. Harvath(1976) reported that with low nozzle velocities resulted in a two-peak distribution, which persisted to be broad until a certain velocity was reached after which smaller uniform drops were produced. Steiner and Hartland(1983) explained this by pointing out that low nozzle velocities result in single drop formation. At higher velocities, additional openings start to operate and some drops are formed by jetting break-up, which corresponds to the second peak in the distribution. Reaching a certain high nozzle velocity, all drops are produced by jetting break-up, and drops become uniform again.

Ward, Loss and Lof(1977) tested the direct contact liquid-liquid heat exchangers in the systems which was associated with solar heated and cooled building to establish the technical feasibility and economic practicality. In this experiment, diethyl phthalate and dimethyl phthalate, butyl benzyl phthalate as dispersed phase liquids were proved to be promising working fluids in the future for their utilization in the direct contact heat transfer.

3. Experimental Methods

Figure 1 is the schematic diagram of the equipment used in the present investigation. The electric heater is filled with the phthalate (working fluid) by 1/18 HP circulation pump (① → ②). Phthalate is heated to the desired temperature and



B = Brass Pipe to keep Thermocouples Centered
C = Column
D = Data Logger
F = Flowmeter
I = Interface between Water and Phthalate
S = Free Phthalate Surface
H = Heater Tank
T = Phthalate Tank
WS = Water Supply
⊗ = Ball Valve

Pu = Pump (1/18 PS)
Th = Thermocouples
V_i = Inlet Valve
V_o = Outlet Valve
TD = Heater Tank Drain
MD = Main Drain
● = Thermocouple
⋈ = Glove Valve

Fig. 1 Experimental Set-Ups

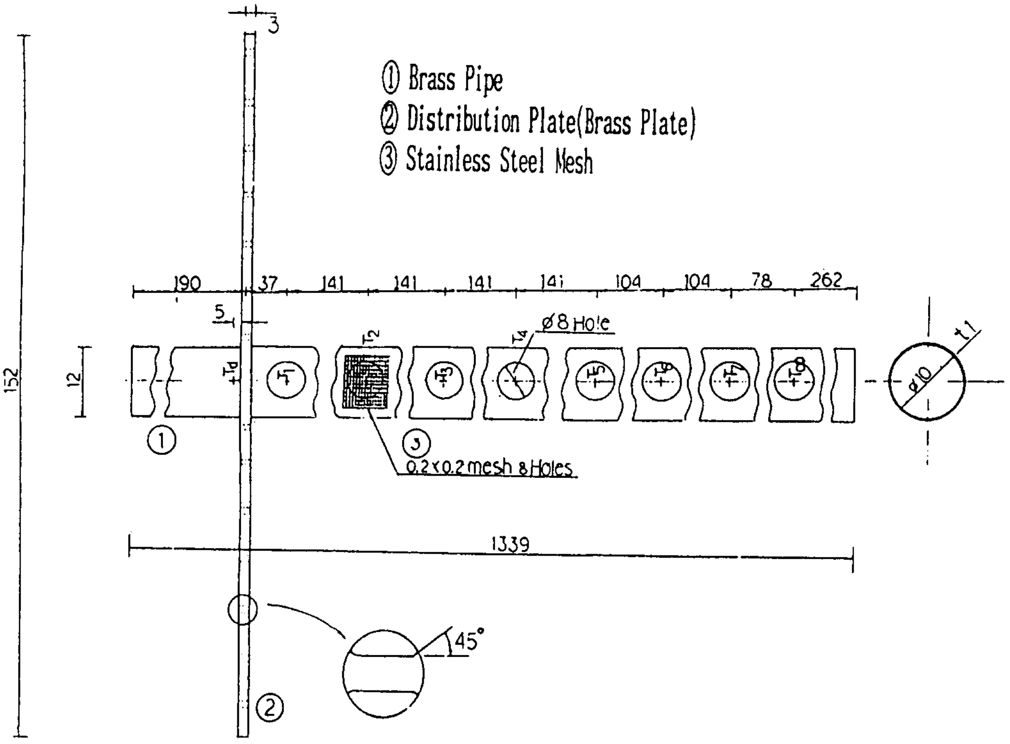


Fig. 2 Distribution plate and locations of thermocouples

after passing through the flowmeter (② → ③), Phatalate is dispersed into the water column through the distribution plate located at the upper part of the column (③ → ④ → ⑤). After phthalate drops are injected down into the water column and travel down through the column, they are collected in the bottom part of the column to be discharged again through the outlet (⑤ → ①).

The column is made of pyrex glass, 120 mm in diameter, 1383 mm in height and 3 mm in thickness. The electric heater is set to give constant temperature by T4M type temperature controller. The distribution plate is made of 3 mm brass with 44 holes (1 mm in diameter). The distance between holes is 15 mm and the plate has one hole for each 2.25 cm^2 of surface area. The flowmeter is an infinitesimal-flow controlled type, which is calibrated to directly measure flowrates. The copper-constantan thermocouples are placed inside of a brass pipe along the center line of the column to measure the temperatures of water as shown in Fig. 2.

The perforated plate at the top of the unit distributes the incoming hot liquid across the entire horizontal surface of the water. As this liquid streams through small holes in the plate and reaches the water surface, it breaks up into small, nearly spherical drops, affording a large heat transfer area per unit volume of water. As drops pass down through the column of water heat is transferred from them to the water phase, and the drops are collected into a liquid pool under the water, which supplies the collector pump.

At this time, the inlet folwrate is adjusted continually to keep the boundary of water-dispersed working fluid constant, and to make the inlet flowrate equal to that of the outlet flowrate to maintain steady state operation. Then, the temperature is measured and holdup rates are determined. During this operation, the temperature of the continuous phase liquid reaches that of the dispersed phase liquid collected separately in the bottom part.

The column inlet temperature of the dispersed working fluid is maintained to be about 85℃, and the inlet flowrates of diethyl phthalate (viscosity : 0.024•g/cm•sec, specific heat : 1.57 J/g•℃, conductivity : 1295 J/sec•cm•℃ at 85℃) and dimethyl phthalate(viscosity : 0.024 g/cm•sec, specific heat 1.55 J/g•℃, conducctivity : 1344 J/sec•cm•℃ at 85℃) are varied to give 5, 10, 15, 20, 25, 30 cm^3/sec. During the experiments, two different air spaces (4 cm and 8 cm) between the distribution plate and the water surface are considered to observe the effects of air spacing on the formation of liquid drops.

4. Experimental Results and Discussions

4.1 Dispersed phase drop size distributions

The mechanism of the drop formation for the dispersed working fluid determines the drop size which is closely connected with the thermal performace of the direct contact heat exchanger, According to previous findings, the drop sizes most effective to maximize heat transfer rates are in the range of 1 mm to 2 mm in diameter. The column was operated with the water level about 4 cm and 8 cm below the distribution plate to observe the effects of the air space on drop formation

As the dimethyl phthalate streams through small holes in the distribution plate and reaches the water surface, it breaks into small drops and pass down through the water column. Drops are formed by two distinct mechanisms when liquid is discharged from a hole. The first is dropwise mode of formation at low flowrates up to volumetric flow rates of 10 cm^3/sec at the temperature of 85℃. As the flowrates are increased exceeding 10 cm^3/sec, the drops begin to form through jet break-ups (jet-wise mode of formation). Similar phenomena have been observed by Steiner and Hartland(1983). The measurement of drop sizes is done by measuring the drops in the vertical dimension because of horizontal distortion effects due to the curvature of the column.

Fig. 3 Photograph of dimethyl phthalate droplet formations for 4 cm air space and 15 cm^3/sec flowrate

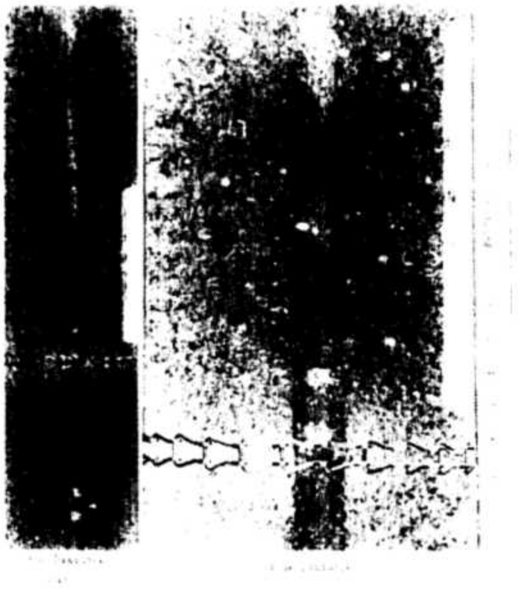


Fig. 4 Photograph of diethyl phthalate droplet formations for 4 cm air space and 25 cm^3/sec flowrate

The typical drop formations of dimethyl

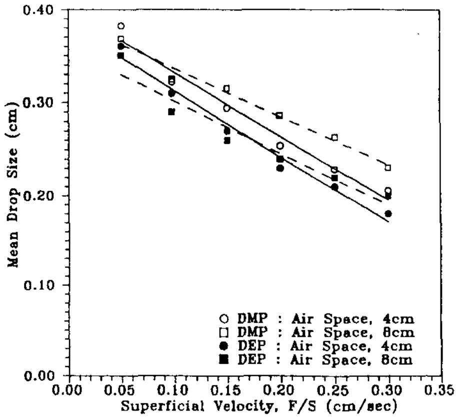


Fig. 5 Mean drop sizes of dimethyl phthalates and diethyl phthalates

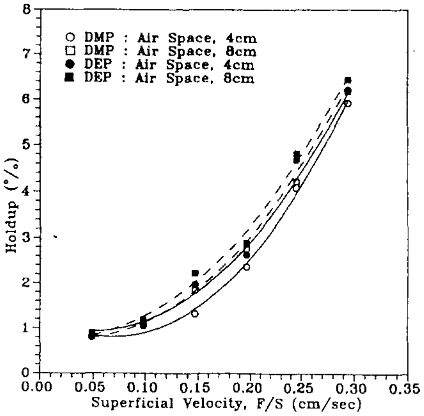


Fig. 6 Holdup values with various flowrates

phthalate and diethyl phthalate during the experiments are shown in Figs. 3 and 4. In the case of the 4 cm air spacing, rather uniform drops are observed for low flowrates. However, the drop size tends to decrease as the flowrate increases. For the flow rates above 25 cm^3/sec, the column is densely filled with rather small uniform drops. Figure 5 shows the relationship between drop formation and superficial velocities (F/S), which are the dispersed phase liquid flowrates divided by the cross sectional area of the column. For the flowrates below 10 cm^3/sec, the drop sizes are approximately 3 mm to 5 mm, while the drop sizes are 1.5 mm to 3 mm for flow rates above 10 cm^3/sec. The overall drop formations for both 8 cm and 4 cm air spacings show similar characteristics.

4.2 The holdup of the dispersed phase

Holdup is defined as the fraction of the effective volume of the heat exchanger occupied by the dispersed phase. Holdup is considered to be dependent on flowrates, liquid system properities, operating temperatures, and drop sizes. Holdup is an important parameter which determines relative velocity and evaluates total contact surface area between continuous phase and dispersed phase drops. The procedure adopted for determining the holdup rate of phthalate is done by measuring the position of the water-phthalate interface in the bottom of the column, the air-water interface at the top of the column, and the air-phthalate interface above the distribution plate. The distance between the water-phthalate and air-water interface (L) times the column cross sectional area has been used as the effective column volume.

The holdup volume was measured by subtracting the change in the air-phthalate interface from the change in the water-phthalate interface and multiplying by the column cross sectional area when the operation is stopped. The holdup volume divided by the effective column volume is the holdup value experessed as a decimal fraction. Figure 6 shows the relationship between the superficial velocities and the holdup values measured in this way.

4.3 Temperature measurements

No temperature stratification was observed in the heat exchanger column. All thermocouples were in contact with the water and showed identical temperatures reaching the final stage of the experiments. The temperature of the phthalate drops was not measured directly but the drop temperature at the bottom of the column was equal to the water temperautre at that location.

It was observed that there was no thermal stratification in the heat exchanger column. For a rational size heat storage tank, the required flowrates per unit volume of the heat exchanger are so high that even thermal stratification resulting from several hours of non use will be quickly

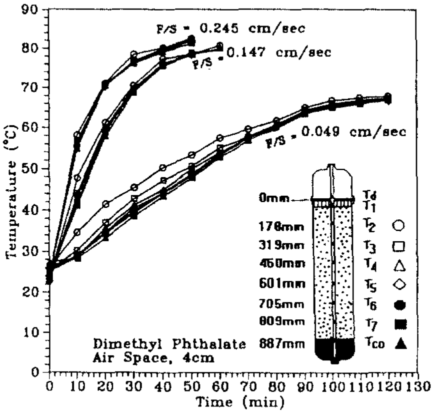


Fig. 7 Temperature measurements with dimethyl phthalate for 4 cm air space

destroyed as soon as pumping begins. Because of the close resemblance between the direct contact liquid-liquid heat exchanger and ordinary hot water heat storage tanks, it is clear that their behavior from a temperature stratification standpoint would be expected to be essenitially same. Consequently the lack of temperature stratification in the direct contact liquid-liquid heat exchanger does not consititute a disadvantage when compared with ordinary hot water heat storage tanks.

It is clear that the water depths used were more than enough to transfer all of the heat from the drops under the present experimental conditions and depths of water less than those used here are not likely to encountered in practical situations. Nevertheless it would be desirable to know the minimum depth required and it is hoped that this will be investigated in future works.

Figure 7 is the temperature profile of dimethyl phthalate with 5 cm^3/sec, 15 cm^3sec, and 25 cm^3/sec flowrates for the 4 cm air space. For the 5 cm^3/sec flowrate, the temperature of the continuous phase fluid increased 0.5℃ /min during the first 20 minute, 0.4℃ /min for the next 60 minute and 0.15℃ /min thereafter. It implies that there is a slow drift in temperature rise. For the 15 cm^3/sec, the temperature of continuous phase fluid increased 1.8℃ /min during the first 20 minute, 0.8℃ /min for the next 20 minute and 0.2℃ /min thereafter. But for the 25 cm^3/sec, the temperature of continuous phase fluid increased 3.2℃ /min during the first 10 minute, 1.03℃ /min for the next 20 minute, and 0.27℃ /min thereafter.

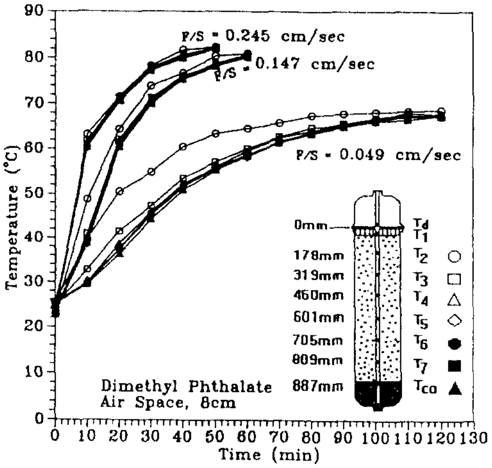


Fig. 8 Temperature measurements with dimethyl phthalate for 8 cm air space

The heat exchanger reached its thermal equilibrium at 67℃ after 120 minute of operation for the 5 cm^3/sec, 80℃ after 60 minute for the 15 cm^3/sec and 81℃ after 50 minute for the 25 cm^3/sec respectively. The final temperature of the continuous phase seems to increase rapidly as the flowrate increases.

Figure 8 shows the temperature measurement of

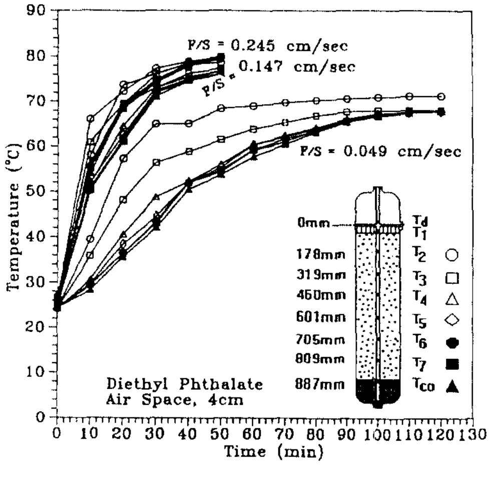


Fig. 9 Temperature measurements with diethyl phthalate for 4 cm air space

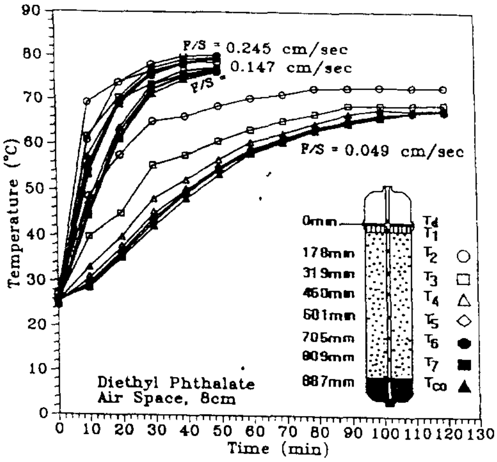


Fig. 10 Temperature measurements with diethyl phthalate for 8 cm air space

dimethyl phthalate with the flowrates of 5 cm^3/sec, 15 cm^3/sec, and 25 cm^3/sec for the 8 cm air space. The temperatures measured are similar to those of the 4 cm. The temperature pofile of the diethyl phthalate for the air space of 4 cm and 8 cm are shown in Figs. 9 and 10.

4.4 Heat transfer results

In Fig. 11 principles of heat transfer mode between indirect and direct contact heat exchangers are explained and in the direct contact heat exchanger, the overall heat transfer coefficient (U) depends on the heat transfer coefficients on the inside (h_d) and ouside (h_c) of the dispersed phase drop. Tables 1 and 2 contain the heat transfer calculations for dimethyl phthalate and diethyl phthalate. Also, in the case that the bulk of the resistance to heat transfer lies in the inside dispersed phase drop ($h_c \gg h_d$), the heat transfer coefficient of drop inside (h_d) can be obtained by Handlos and Baron's(1957) Eq. (1)

Table 1 Heat transfer results for dimethyl phthalate

Air space cm	F cm^3/sec (1)	ΔT ℃ (2)	U J/cm^2sec℃ (3)	h_d J/cm^2sec℃ (4)	U_V J/cm^2sec℃ (5)	N_N (6)	N_{pe} (7)	aN_S cm^{-1} (8)	2/L cm^{-1} (9)
4	25	6.3	0.01083	0.00447	0.01125	1.86	1837.9	0.0263	0.02
	15	11.3	0.02321	0.00740	0.00675	5.16	3937.5	0.0263	0.027
	5	18.6	0.01599	0.00417	0.00225	4.36	2712.6	0.0263	0.027
8	25	5.4	0.01141	0.00414	0.01125	2.23	1936.1	0.0263	0.027
	15	11.5	0.02009	0.00610	0.00675	4.69	3407.3	0.0263	0.027
	5	17.5	0.01442	0.00377	0.00225	3.91	2446.6	0.0263	0.027

Table 2 Heat transfer results for diethyl phthalate

Air space cm	F cm^3/sec (1)	ΔT ℃ (2)	U J/cm^2sec℃ (3)	h_d J/cm^2sec℃ (4)	U_V J/cm^2sec℃ (5)	N_N (6)	N_{pe} (7)	aN_S cm^{-1} (8)	2/L cm^{-1} (9)
4	25	5.3	0.00840	0.00365	0.01073	1.29	1424.7	0.0263	0.02
	15	8.2	0.01631	0.00530	0.00644	3.35	2768.1	0.0263	0.027
	5	17.5	0.01553	0.00404	0.00215	3.99	2635.5	0.0263	0.027
8	25	5.5	0.00853	0.00343	0.01073	1.41	1448.1	0.0263	0.027
	15	8.3	0.01461	0.00471	0.00644	3.02	2478.8	0.0263	0.027
	5	17.5	0.01395	0.00376	0.00215	3.45	2367.0	0.0263	0.027

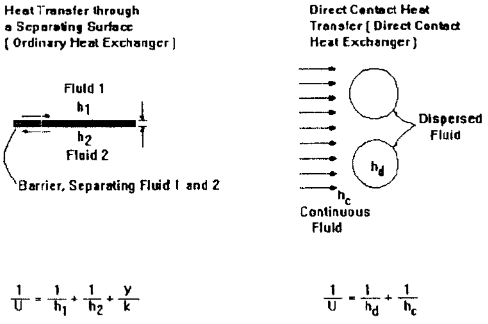


Fig. 11 Heat transfer modes for indirect and direct contact heat exchangers

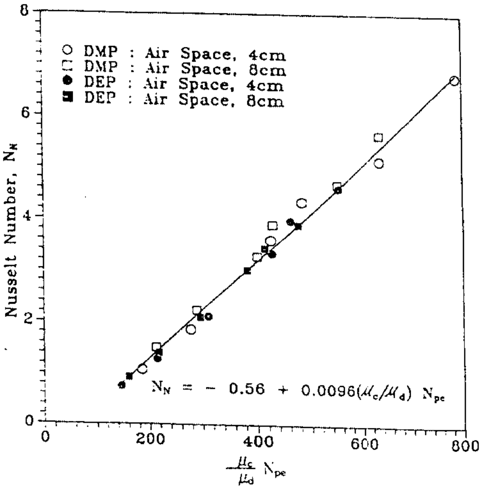


Fig. 12 Heat transfrer results for the direct contact Liquid-Liquid heat exchanger

$$N_N=\frac{0.00375}{1+(\mu_c/\mu_d)}N_{pe}. \tag{1}$$

It appears clear that the overall heat transfer coefficient (U) is approximately equals to the heat transfer coefficients of the inside dispersed phase drop (h_d) in the heat transfer calculations results of Tables 1 and 2. Therefore, it appeares reasonable that the most resistance to heat transfer lies in the inside of dispersed phase drop. So, the overall heat transfer coefficient, U of the direct contact heat exchanger may be reduced to

$$U \cong h_d \quad \text{for } h_c \gg h_d. \tag{2}$$

It is noted that column 6 and 7 show identical values, so that

$$a\,N_s=2/L \tag{3}$$

and the Stanton number, N_s becomes by Eq. (2)

$$N_s=h_d/(c_d\rho_d F/S) \cong U/(c_d\rho_d F/S). \tag{4}$$

Combining Eqs. (3) and (4), one obtains volumetric heat transfer coefficient, U_v is defined as the product of the overall heat trasfer coefficient, U and the interfacial area of the dispersed phase and the continuous phase per unit volume, a.

$$U_v=(2/L)c_d\rho_d(F/S). \tag{5}$$

In other words, the mean log temperature difference is a half of the initial temperature difference of the dispersed phase fluid and continuous phase fluid (water) because the temperature of dispersed phase leaving the direct contact liquid-liquid heat exchanger becomes same as the one continuous phase. Consequently,

$$Q=UA\Delta T_1/2=UaV\Delta T_1/2$$

$$=UaSL\Delta T_1/2=c_d\rho_d(F/S)S\ \Delta T_1. \tag{6}$$

Rewriting Eq. (6) for the volumetric heat transfer coefficient,

$$U_v=(2/L)c_d\rho_d(F/S). \tag{7}$$

Therefore, Eq. (7) is found same as the Eq. (5). It appears reasonable to assume the mean log temperature difference is a half of the initial temperature difference.

In generally, Nusselt number, N_N, had been presented as a function of N_{pe}, but it has been justified that be reasonable to consider the effect of μ_c and μ_d from the experiment result of Handlos and Baron(1957), Ward and Loss(1977). Therefore, N_N is plotted as a function of (μ_c/μ_d) N_{pe} in this work. In Fig. 12, It can be represented with the following linear equation for dimethyl phthalate and diethyl phthalate for both 4 cm and 8 cm air spaces.

$$N_N=-0.56+0.0096\ (\mu_c/\mu_d)N_{pe}$$
$$140 \leq (\mu_c/\mu_d)N_{pe} \leq 780. \tag{8}$$

5. Conclusions

(1) In comparison with the direct contact heat exchanger using the working fluid lighter than water, the arrangement utilizing the heavier working fluids such as phthalates ensures stable water

interface at the top of the column during the entire operation of the heat exchanger.

(2) When the heat exchanger reaches its thermal equilibrium, the average temperature difference between the dispersed phase working fluid and the continuous phase fluid can be considered to be a half of that between the inlet dispersed phase fluid and the inlet continuous phase fluid as they reach equilibrium at the bottom of the column. The elapsed time to reach the equilibrium temperature decreases with the increase of flowrates.

(3) The phthalates satisfy necessary conditions as working fluids for the direct contact liquid-liquid heat exchanger by providing large contact areas between the continuous phase fluid and the dispersed phase fluid by small drop formations.

(4) Heat transfer rate of the proposed direct contact heat exchanger is superior to that of the conventional tube and shell heat exchanger. Solar collector corrosion and freezing problems can be easily handled by utilizing the proposed direct contact heat exchanger.

(5) The thermal performance of the two phthalates tested are similar. However, diethyl phthalate is proved to be more useful one as a dispersed working fluid because of its low freezing temperature.

Acknowledgement

This work was supported by the Inha University Gromt, No. 1993-AA014.

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