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INVESTIGATION OF PLATE CONDENSER WITH MULTIPLY LIQUID-SEPARATIONS

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ABSTRACT

In this paper, liquid-separation is attempted to plate condenser to improve the condensation of plate heat exchangers. Liquid-separation plate condenser (LPC) with two paths, three paths and four paths are proposed. The model exhibits good accuracy in predicting heat transfer coefficients (HTC). LPCs show superior performance to conventional plate condenser (CPC). There exists optimum configuration for each LPC, and they are selected for further study. It is found that the more paths LPC has, the higher HTC and heat load (Q) it would be. LPC with three paths and path length ratio (PLR) of 4:3:3 is recommended.

Keywords: Liquid-separation, multiply paths, Plate condenser, PEC.

NONMENCLATURE

Abbreviations	
LPC	Liquid-separation plate condenser
CPC	conventional plate condenser
PEC	performance evaluation parameter
HTC	heat transfer coefficient (W/m^2·K)
CAR	corrugation amplitude ratio
Symbols	
Q	Heat load (W)
Subscripts	
1-4	1-4 path

1. INTRODUCTION

Plate heat exchanger (PHE) has been extensively used in the various processes due to its compactness, high performance, design flexibility and low cost. Although it was invented for single-phase applications, it popularly serves as condenser and evaporator in heat pumps, refrigeration systems and power plants [1]. The superiority of PHE is contributed by enlarged surfaces due to different patterns of corrugation and high turbulence at relatively low flowrates, which leads to its high heat transfer coefficient (HTC).

PHE is a promising candidate as the condenser since the corrugations could break up the condensate and improve heat transfer [2]. Han et al. [3] discovered that the larger chevron angle resulted in stronger turbulence and more abrupt changes of the flow, leading to higher HTC. Arsenyeva et al. [4] proposed new plate condenser with several differently corrugated sections as variable cross areas. It could reduce pressure drop by 40% without much penalty to HTC. The conventional plate condenser (CPC) has an issue of condensate accumulation at the middle low part of channel. This attributes to degradation of HTC owing to the increasing thickness of liquid film and thermal resistance. It has been demonstrated that HTC at the bottom wall surface can be 5-10 times lower than that at the top surface [5]. Hence if the liquid film thickness is reduced, a higher HTC at lower part of the plate can be expected.

Liquid-separation condensation, proposed by Peng et al. [6], aims to promptly drain away the condensate during condensation, which consequently increases the vapor quality that improves heat transfer and decreases the mass flowrate that benefits decrease of pressure drop. Zhong et al. [7] revealed that the liquid-separation condenser could have higher HTC and lower pressure drops at the same time. Li and Hrnjak [8] stated that the liquid-separation condenser led to higher condensate flow rate and lower outlet temperature. The liquid-separation condensation has been widely studied in fin-and-tube condenser. Little attentions have been paid on the PHE working as a condenser with liquid-separation.

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In this paper, liquid-separation condensation is implemented in plate condenser, abbreviated as LPC. Multiply paths (two paths, three paths and four paths) are introduced. It aims to reveal the effectiveness of applying the liquid-separation in plate condenser.

2. MODELS

2.1 Physical model

In CPC, as the condensation occurs, vapor converts into liquid. With the interference of gravity, more condensate accumulates at lower part of the channel, which results in lower values of HTC, as shown in Fig. 1(a). When implementing the liquid-separation, the condensate is drained out from the channel without entering to the next path. Therefore, the flow in the next path would have higher vapor quality, and the flow condition also would be more like in the previous path. As a result, its HTC is significantly increased owing to the improved vapor quality and reduced liquid film on the wall surface. Fig. 1(b)-(d) are schematically indicting the LPC with two paths (liquid drainage once), three paths (liquid drainage twice) and four paths (liquid drainage three times). Moreover, it has to point out that the distributions of the path length of LPC does not necessary to be equal as presented in Fig. 1, which relates to LPC performance. Therefore, PLR has to be optimized to obtain the best performance.

HTC of refrigerant ($\mathrm{HTC_r}$) and water ($\mathrm{HTC_w}$) are from Longo et al. [9] and Yan et al. [10].

$$\mathrm{HTC_r} = \mathrm{HTC_{sat}} + \left(\frac{T - T_{\mathrm{sat}}}{T_{\mathrm{sat}} - T_{\mathrm{wall}}}\right)\left(\mathrm{HTC_{liq}} + \frac{c_{\mathrm{p}} q}{\gamma}\right),$$

$$Re_{\mathrm{eq}} \geq 1600 \tag{1}$$

$$\mathrm{HTC_r} = 0.943\varphi\left[\frac{\lambda_{\mathrm{liq}}^3 \rho_{\mathrm{liq}}^3 g\gamma}{\mu_{\mathrm{liq}} L\left(T_{\mathrm{sat}} - T_{\mathrm{wall}}\right)}\right]^{1/4}, \; Re_{\mathrm{eq}} < 1600 \tag{2}$$

$$\mathrm{HTC_w} = 0.2121\left(\frac{\lambda_{\mathrm{w}}}{D_{\mathrm{h}}}\right) Re^{0.78} Pr^{1/3} \tag{3}$$

The correlations of the pressure drop of the refrigerant and water are found in [11] and [12].

The performance evaluation parameter (PEC) is employed to identity the effectiveness of LPC [13].

$$\mathrm{PEC} = \frac{\mathrm{HTC_{r,ave,LPC}} / \mathrm{HTC_{r,ave,CPC}}}{\left(\Delta p_{\mathrm{r,fr,\,LPC}} / \Delta p_{\mathrm{r,fr,CPC}}\right)^{1/6}} \tag{4}$$

More details are found in Ref. [14]. Owing to the unavailability of LPC experimental data, the calculations and measurements, which based on experimental results of CPC with R410A in [11], are compared, as shown in Fig. 2. It is clear that errors are within ±25%, showing fair agreements. Moreover, dividing CPC into multiply paths has insignificant influence.

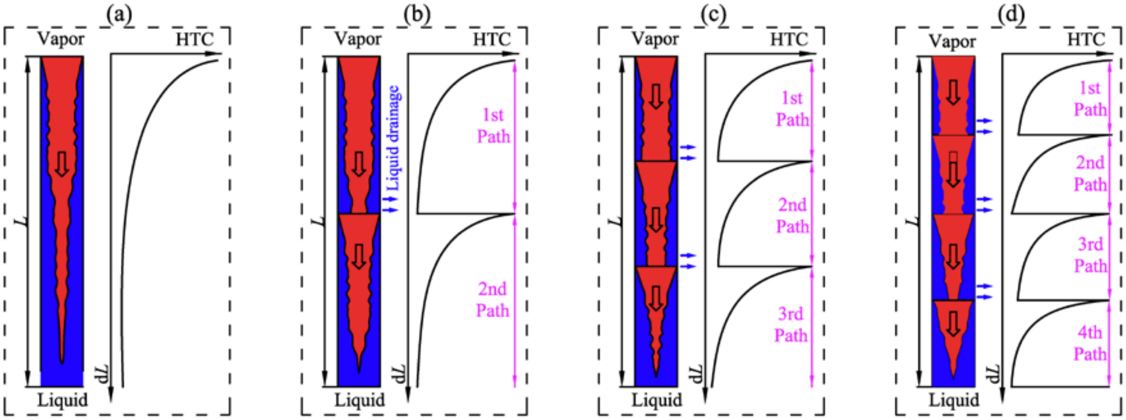

Fig 1 Illustrations of phase change and HTC in (a) CPC and LPC with (b) two paths, (c) three paths and (d) four paths

2.2 Mathematical model

For simplify, following assumptions are listed as:

- The flow is steady and one-dimensional.
- The condensate and the vapor refrigerant are effectively separated.
- The wall temperature of each path is the same.
- Plate thermal resistance is ignored.

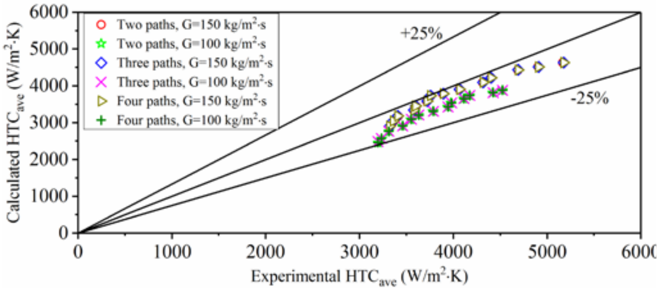

Fig 2 Molel validation

3. RESULTS AND DISCUSSIONS

3.1 Configuration optimization

The positions of liquid-separation units are essential to the afterwards flow rates and heat transfer that are directly related to the LPC performance. Thus it has to determine the length of each path, indicated by path length ratio (PLR) that is defined as each path length divided by entire path length, to get maximum PEC.

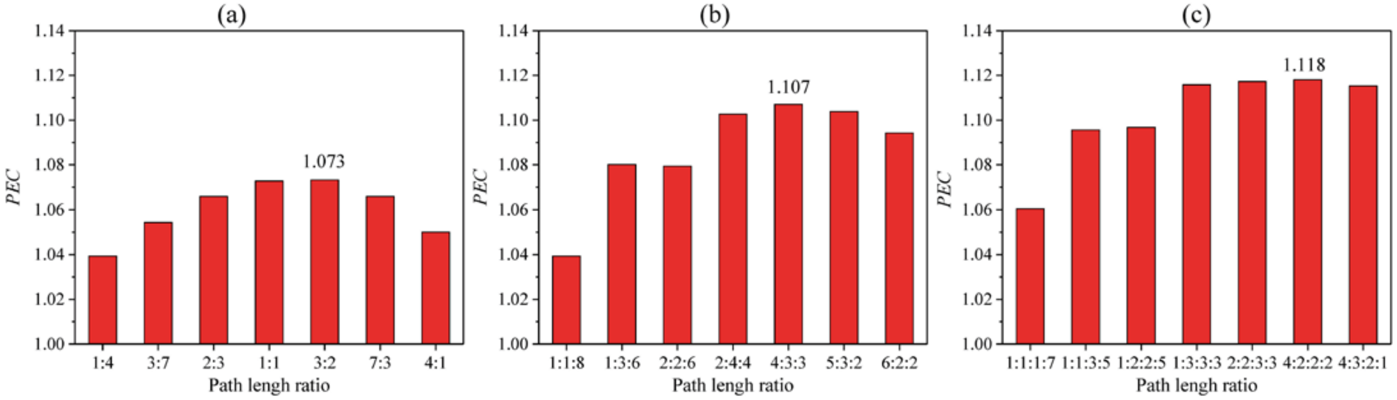

Fig 3 Performance of LPC with (a) two paths, (b) three paths and (c) four paths when varying path leng ratio

The plate length and width are set as 479 mm and 116 mm, respectively, and corrugation amplitude is 2.9 mm. R410A is selected with inlet temperature of 30 ^{o}C, vapor quality of 1 and mass flowrate of 0.07 kg/s [14]. Fig. 3 gives the effects of PLR on PEC for the LPC with multiply paths. It is clear that all configurations have PEC higher than 1, meaning its superior to CPC. Moreover, there exists an optimum PEC for each LPC. LPCs with two paths, three paths and four paths achieve their optimum performance when PLR is 3:2, 4:3:3 and 4:2:2:2, respectively. For simple, three PLCs are named as LPC-A, LPC-B and LPC-C. According to the magnitude of PEC, LPC-C has the best performance, followed by LPC-B, and then LPC-A. This is to say that more times of the liquid-separation apply, the better performance of LPC would be. This can be explained by the enhanced vapor quality due to the drainage of condensate, which is beneficial to heat transfer. Note that the results are obtained at the condition of equivalent mass flux of refrigeration through each path, which is similar as CPC. Furthermore, since the condensate is drained away, the mass flowrate is reduced. Thus the corrugation amplitudes in the second path, third path and fourth path have to be narrowed to accommodate the unchanged mass flux. Therefore, the distribution of corrugation amplitude of in LPC-A, LPC-B and LPC-C are different. This is because the different path length results in different heat transfer area (A) and amount of uncondensed vapor to the next path, hence the smaller corrugation amplitude occurs. It has to point out that the more paths will lead to the extreme small corrugation amplitude, which causes the problem of manufacturing the plates. Thus the LPC with five or more paths are not discussed in this study.

3.2 Performance comparisons

Since the optimum configurations of LPCs with two paths, three paths and four paths have been decided as LPC-A, LPC-B and LPC-D, it is of interest to discover more insights of these three LPCs.

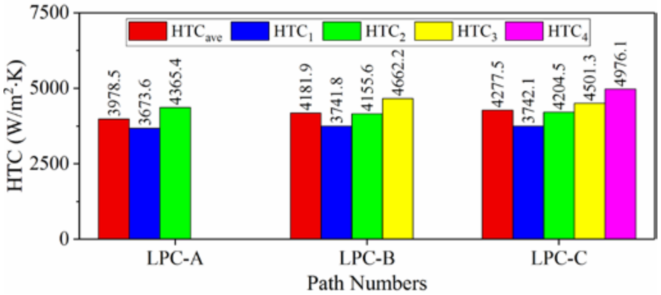

Fig 4 Details of HTC in difference LPCs

Fig. 4 shows HTC in each path of three LPCs. Clearly, at the first path, HTC$_1$ of LPC-A is lower than that of LPC-B and LPC-C which have similar HTC$_1$. This is interpreted as: LPC-A has much longer first path than that of LPC-B and LPC-C, leading to larger A and more condensed vapor as well as lower vapor quality. Given that vapor quality at the inlet is the same, its average vapor quality is therefore lower, results in the smaller HTC. LPC-B and PLC-C has similar HTC with HTC$_1$ owing to the same first path length. For HTC$_2$, it is larger than HTC$_1$ since the second path is shorter than that in the first path, causing large average vapor quality. For the third path and fourth path, although they have the same path length as the second path, HTC$_3$ and HTC$_4$ are further improved due to the difference conditions at the water side in the neighboring channel. As a result,

HTC_{ave} of LPC-C is 6.3% and 1.1% than that of LPC-A and LPC-B, respectively.

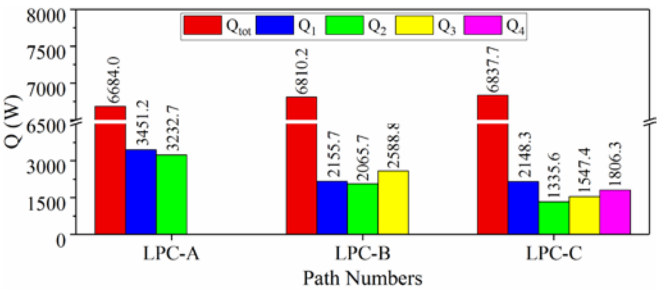

Fig 6 Details of heat load in difference LPCs

Fig. 5 indicates the distributions of heat load (Q) in each path in these LPCs. In LPC-A, it is obvious that Q in the first path (Q_1) is slightly higher than Q_2. This can be explained as: although A of the first path (A_1) is 50% larger than A_2, HTC_1 is 15.8% lower than HTC_2, leading to only 6.7% of Q_1 over Q_2. Regarding LPC-B, Q_1 and Q_2 have similar characteristics. However, Q_3 is 25.3% higher than Q_2 despite of the same A_2 and A_3, which is mainly contributed by the larger HTC_3. As for LPC-C, for same reason, Q_2, Q_3 and Q_4 are gradually augmented, while the significantly high Q_1 is dominated by twice A_1 to others. If compared to heat load of the entire plate (Q_{tot}), it is discovered that Q_{tot} of LPC-C is largest, whereas the difference of Q_{tot} is insignificant in LPC-B and LPC-C. The main reason for this can be derived from HTC_{ave} in Fig. 4. Hence, it can say that LPC-B is superior to LPC-A and LPC-B in terms of high performance.

4. CONCLUSIONS

LPCs with multiply paths are investigated to enhance the condensation of plate heat exchanger. The optimum configurations of LPCs are determined and compared. It is found that LPCs with multiply paths always have PEC greater than 1. LPCs with two paths, three paths and four paths have their maximum PEC when PLR is 3:2, 4:3:3 and 4:2:2:2, respectively. LPC with three paths has the highest HTC_{ave} and Q_{tot}.

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