Application of closed-loop oscillating heat-pipe with check valves (CLOHP/CV) air-preheater for reduced relative-humidity in drying systems

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Abstract

This paper aims to design, construct, and test the CLOHP/CV air-preheater for reduced relative humidity in drying systems for recovering the waste heat from the drying cycle. The CLOHP/CV heat-exchanger consisted of 3.58 m long copper tubes, with an internal diameter of 0.002 m. The evaporator and condenser sections were 0.19 m long, the adiabatic sections were 0.08 m long, the hot-air velocities were 0.5, 0.75 and 1 m/s with the hot-air temperatures being 50, 60 and 70 °C, and the relative humidity was 100%. The working fluid was R134a with the filling ratio of 50%. It can be concluded that, with an increase in the hot-air temperature from 50 to 70 °C, the heat-transfer rate slightly increases. The velocity increases from 0.5, 0.75 to 1 m/s and the heat-transfer rate slightly decreases. The velocity increases from 0.5, 0.75 to 1 m/s and the effectiveness slightly decreases. The hot-air temperature increases from 50 to 70 °C and the effectiveness slightly increases. The relative humidity reduced to the range 54–72% from 89% to 100%. The CLOHP/CV air-preheater can reduce the relative humidity and achieve energy thrift.

Keywords: Closed-loop oscillating heat-pipe; Check valves; Air-preheater; Relative humidity; Heat recovery; Drying system

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Nomenclature

A	area (m^2)
Bo	Bond number $D_i\left[g\left(\frac{\rho_l-\rho_v}{\sigma}\right)\right]^{\frac{1}{2}}$ (–)
C_p	specific heat at constant pressure (J/kg K)
C_v	number of check valves (–)
D	diameter (m)
Fr	Froude number $\frac{Q_m^2}{\rho_v^2 h_{fg}^2 D_i^5 g}$ (–)
g	gravitational acceleration (m/s^2)
h_{fg}	latent heat of vaporization (kJ/kg)
Ja	Jacob number $\frac{h_{fg}}{Cp_l T_v}$ (–)
Ku	Kutateladze number $\left(\frac{q}{h_{fg}\rho_v(\rho_g(\rho_l-\rho_v)/\rho_v^2)^{1/4}}\right)$ (–)
k	thermal conductivity (W/m K)
L	length (m)
Pr_v	Prandtl number of vapor $\left(\frac{C_{pv}\mu_v}{k_v}\right)$ (–)
Q	heat-transfer rate (W)
q	heat flux (W/m^2)
R_{cv}	ratio of number of check valves to number of capillary tubes (–)
RH	relative humidity (%)
T	temperature (°C)
V	velocity (m/s)
We	Weber number $\frac{Q_m^2}{\rho_v h_{fg} D_i^3 \sigma}$ (–)

Greek symbols

μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

c	cold
e	evaporator
i	inside, inlet
l	liquid
o	outlet
t	total
v	vapor

1. Introduction

The aim of the dryer is to reduce moisture content of the produce. Traditionally, the application of a heat-pipe air-preheater for the dryer is unable to use its waste heat with a closed system and does not employ the relative humidity (RH) in any drying systems. In the application of closed-loop oscillating heat-pipe with check valves (CLOHP/CV) air-preheater for relative humidity control in drying systems, there are many advantages:

e.g. large quantities of heat are transported through a small cross-section area. The CLOHP/CV is a very effective heat-transfer device invented by Akachi et al. [1]: it has a simple structure and fast thermal-response. The CLOHP/CV consists of a long capillary tube bent into many turns, and the evaporator section, adiabatic section, and condenser section are located at these turns, with the ends joined to form a closed loop. It incorporates one or more direction-control one-way check valves in the loop so that the working fluid can circulate in the specified direction only. Miyazaki et al. [3] studied the oscillating heat-pipe with check valves. It was found that the CHOHP/CV has a high rate of heat transfer. Pipatpaiboon [4] studied the effect of inclination angle, working fluid and the number of check valves on the characteristics of heat transfer in a closed-loop oscillating heat-pipe with check valves. It was found that the CLOHP/CV equipped with two check valves has the highest heat-transfer capacity. Pipatpaiboon [5] devised a correlation for predicting the heat transfer of a closed-loop oscillating heat-pipe with check valves (CLOHP/CV). Rittidech et al. [6] studied the closed-ended oscillating heat-pipe (CEOHP) air-preheater for energy thrift in the dryer. It was found, from the experimental results, that the thermal effectiveness increases and the (CEOHP) air-preheater achieves energy thrift. Wu et al. [7] studied the application of heat-pipe exchangers for humidity control in an air-conditioning system. It was observed that this type of heat exchanger can be an advantageous replacement for a conventional reheat coil, resulting in energy saving and enhancing the cooling capability of the cooling coils with little or no external energy need.

The principle of operation is similar to that of an air-preheater by the CLOHP/CV, which is widely accepted as the most efficient heat-transfer device for high heat-loads [1]. It has the capability of operating in any position and has operational flexibility. At present, the CLOHP/CV does not sufficiently solve energy problems. So, an improvement

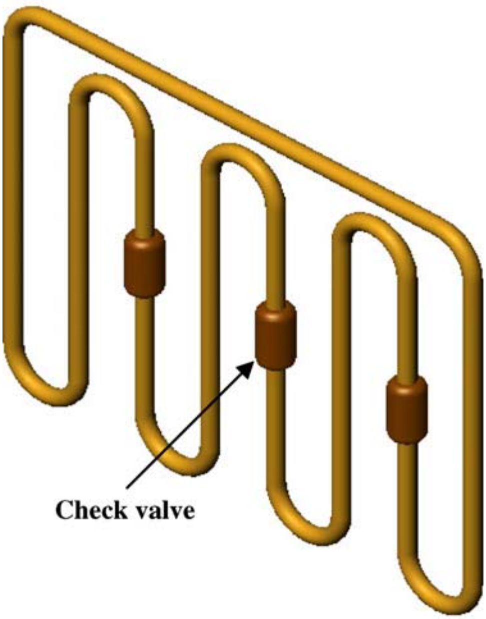

Fig. 1. Closed-loop oscillating heat-pipe with check valves (CLOHP/CV).

of the heat-pipe air-preheater for the dryer is needed. In the application of the closed-loop oscillating heat-pipe with check valves (CLOHP/CV) air-preheater for relative humidity control in drying systems, a very effective heat-transfer device has been found. It incorporates one or more direction-control one-way check valves in the loop, so that the working fluid can circulate in a specified direction only as shown in Fig. 1.

This paper aims is to design, construct and test the CLOHP/CV air-preheater for reduced relative humidity in drying systems for recovering the waste heat from the drying cycle.

2. The check valve

The check valve is a floating-type valve that consists of a stainless ball and copper tube, in which ball stopper and conical valve seats are provided at the ends, respectively. The ball can move freely between the ball stopper and the valve seat as shown in Fig. 2.

3. The conventional drying cycle

The basic principle of the drying process is to heat the fresh air by an electric heater. Then, the hot air moves through the layer of product in the chamber. The heat is transferred to the product for reducing its moisture as shown in Fig. 3.

4. Design of the CLOHP/CV air-preheater system and calculator concept

- Design the parameters, e.g. the maximum heat-transfer rate of the heat pipe heat exchanger for the drying system (Q_{max}, W), as follows:

$$\begin{aligned} Q_{\max} &= C_{\min}(T_{hi} - T_{ci}) \\ C_{\min} &= \rho VAC_p \end{aligned} \tag{1}$$

- The inner diameter of the CLOHP/CV is calculated by Meazawa et al. [2]:

$$D_{\max} \leqslant 2\sqrt{\frac{\sigma}{\rho_{1g}}} \tag{2}$$

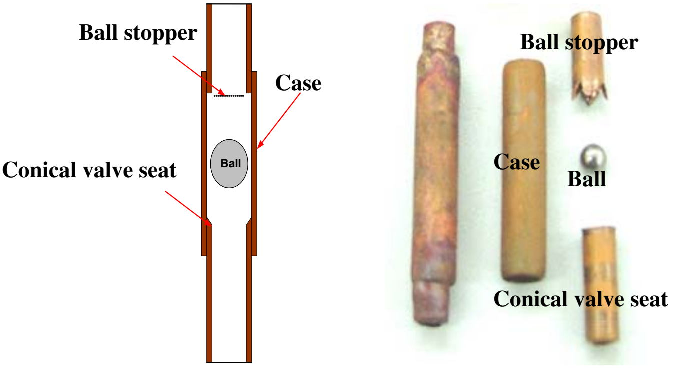

Fig. 2. The check valve.

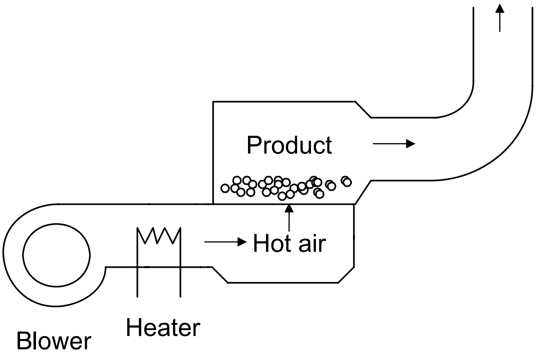

Fig. 3. The conventional drying cycle.

- Select the type of working fluid that is appropriate to the operation temperature.
- Select the working temperature to be used in the drying system.
- Calculate the heat-transfer rate ($Q_{\mathrm{max,W}}$) from Ku_{90}, and the heat flux (q, W/m^2).
- L_e, L_a, L_c, L_t and n are defined as the duct size of the dryer.
- The velocities are 0.5, 0.75 and 1 m/s.
- Bo, Fr_v, Ja, Pr, R_{cv}, We, ρ_v, ρ_l and $\frac{L_e}{D_i}$ are described and the heat flux of the CLOHP/CV air-preheater is solved by the correlation from [5]. The standard deviation of this equation is ±30%.

$$Ku_{90} = 0.0004\left[Bo^{2.2}Fr^{1.42}Ja^{1.2}Pr^{1.02}\left[\frac{\rho_v}{\rho_l}\right]^{0.98}R_{cv}^{1.4}We^{0.8}\left[\frac{L_e}{D_i}\right]^{0.5}\right]^{0.107} \tag{3}$$

The heat-transfer rate (Q, W) is calculated from Ku_{90}, and the heat flux (q, W/m^2) calculated, as shown in (4)

$$Q_{90} = (Aq_{90}) \tag{4}$$

Ku_{90} indicates the ratio of heat flux of the CLOHP/CV to the critical heat-flux of the working fluid. It shows whether the obtained heat-fluxes of the CLOHP/CV are more than the critical heat-flux of the working fluid or not, and if pool boiling of the working liquid occurs in the evaporator section of the CLOHP/CV. Bo is the ratio of buoyancy force to the surface-tension force of the working fluid. If $Bo > 1$, this shows that nucleate boiling occurs in the heat-pipe. Fr is the (inertial force)/(gravitational force) and is used in the momentum transfer equations and open-channel flow and wave and surface behavior calculations. Ja is proportional to {(latent heat)/(specific heat at constant pressure)}. Pr_v is the ratio of momentum diffusivity to the thermal diffusivity of vapor slug. If the value is very low, the vapor slug will be able to transfer heat to the condenser section relatively efficiently. Therefore, the value of Ku_{90} or heat flux will be high. ρ_v/ρ_l is the vapor-phase density to liquid-phase density of the working fluid that is influenced by the working pressure and the working fluid within the CEOHP. R_{cv} is the ratio of the number of check valves to the number of turns on a CLOHP/CV. We is proportional to {(inertial force)/(surface tension force)} and is used in momentum-transfer equations, bubble/droplet formation equations and breakage of liquid jets calculations in particular. L_e/D_i defines the size of the CLOHP/CV. For example, if the value of L_e/D_i was very high, then the tube would be large and the evaporator section would

Table 1
The physical parameters of the CLOHP/CV air-preheater

The physical parameter	Description (Set1)	Description (Set2)
Material of tube	Copper	Copper
Inner diameter	0.002 m	0.002 m
Physical dimension of the heat exchanger	$0.2 \times 0.2 \times 0.2$ m (height × length × width)	$0.2 \times 0.2 \times 0.2$ m (height × length × width)
Total length	3.58 m	3.58 m
Evaporator-section length	0.19 m	0.19 m
Adiabatic-section length	0.08 m	0.08 m
Condenser-section length	0.19 m	0.19 m
CLOHP/CV arrangement	Staggered, $S_L = 20$ mm, $S_T = 20$ mm	Staggered, $S_L = 20$ mm, $S_T = 20$ mm
Row number of the CLOHP/CV	$n_L = 11$, $n_T = 10$	$n_L = 11$, $n_T = 10$
Number of turns/set	20	20
Working fluid	R134a	R134a
T_{hi}, T_{ci}	70, 25 °C	70, 25 °C
Working temperature	46.25 °C	46.25 °C
Heat-transfer from correlation [4]	608.19 W	608.19 W
Number of CLOHP/CV	2 Set	5 Set
Total heat-transfer rate from correlation [4]	1216.38 W	3040.95 W

be short. Because of the boiling phenomenon, the value of Ku_{90} or heat flux would be high. If the value of L_e/D_i was very low, then the tube would be small and the evaporator section would be long. Because the boiling phenomenon within this type of tube will be akin to the boiling phenomenon in a confined channel, the values of Ku_{90} or heat flux will be low.

The values of some of these parameters are shown in Table 1.

The effectiveness of the CLOHP/CV air-preheater, ε, is defined as the ratio of the actual heat-transfer rate for an air-preheater heat-exchanger to the maximum possible heat-transfer rate.

5. Experimental set-up

5.1. Prototype

The CLOHP/CV was made of copper tubes. The working fluid was distilled water. The CLOHP/CV heat-exchanger consisted of copper tubes 3.58 m total length per set, with an internal diameter of 0.002 m. The evaporator and condenser sections were 0.19 m long, and the adiabatic sections were 0.08 m long, which is shown in Fig. 4. The physical dimensions of the constructed CLOHP/CV air-preheater are shown in Table 1.

5.2. Test rig

This prototype was installed in a test rig, as shown in Fig. 5. The hot air coming from the heater flows through the CLOHP/CV air-preheater. The initial and final temperatures were measured with thermocouples. Twelve thermocouples of type K were installed on the evaporator section and twelve more on the condenser. These thermocouples were con-

Fig. 4. The prototype: CLOHP/CV air-preheater; and experimental rig.

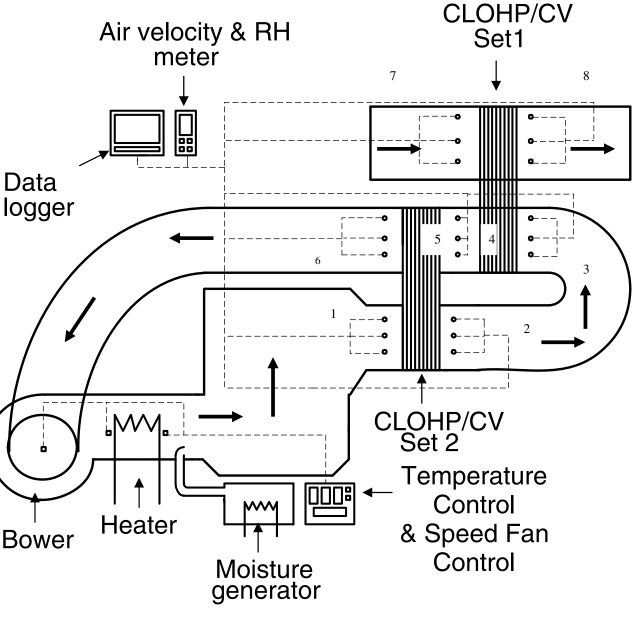

Fig. 5. Test rig: 1, T_{hi}; 2, T_{ho}; 3, T_{hi}; 4, T_{ho}; 5, T_{ci}; 6, T_{co}; 7, T_{ci}; 8, T_{co}.

nected to a Yokogawa-MX100 acquisition data-system. When a steady state was achieved, the temperatures at the inlet and outlet of the evaporator and the condenser section were recorded. The heat-transfer rate and effectiveness were determined and compared with the predicted values.

6. Results and discussion

6.1. Effect of hot-air temperature on heat-transfer rate

Fig. 5 shows the test rig for the CLOHP/CV air-preheater having two sets, and a hot-air velocity of 0.5, 0.75, and 1 m/s. The experimental results present the effect of the hot-air temperature on the heat-transfer rate in Fig. 6. These figures are comparisons made between the experimental results and the predictions from the correlation [5]. It can be seen that, when the hot-air inlet-temperature increases with a lower velocity, the heat-transfer rate also rises. This is because, when the hot-air inlet-temperature increases with a lower velocity, the air outlet-temperature also increases. Thus, the temperature difference between the inlet and the outlet air-temperature also increases and the actual heat-transfer rate will be high. The heat-transfer rate as measured was lower than that predicted via correlation [5]. However, the predictions compare well with the experimental data for the 70 °C run. In addition, when the hot-air temperature increased from 50 to 70 °C, the experimental data were within the standard deviation of ±30% from the correlation predictions. It can be concluded that, if the hot-air temperature increases with a lower velocity, the heat-transfer rate also increases.

6.2. Effect of hot-air temperature on thermal effectiveness

In this experiment, for the CLOHP/CV air-preheater having two sets, the hot-air temperatures were 50, 60 and 70 °C with velocities 0.5, 0.75 and 1 m/s. Fig. 7 shows the effect of the hot-air inlet-temperature on the effectiveness of the CLOHP/CV air-preheater. It can be seen, that when the hot-air inlet-temperature increases with a lower velocity, the effectiveness also rises because the air outlet-temperature also increases. Thus, the temperature difference between the inlet and the outlet air also increases and the actual heat-transfer rate will be high. It can be concluded that, if the hot-air inlet-temperature increases with a lower velocity, the effectiveness also increases as shown in Table 2.

6.3. Effect of velocity on the heat-transfer rate

In this experiment, for the CLOHP/CV air-preheater having two sets, the hot-air velocities were 0.5, 0.75 and 1 m/s with temperatures 50, 60 and 70 °C. Fig. 6 shows the effect of

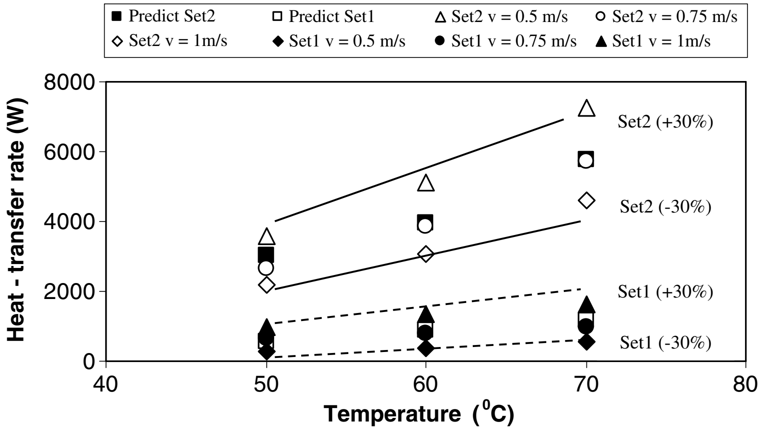

Fig. 6. Effect of hot-air temperature on the heat-transfer rate.

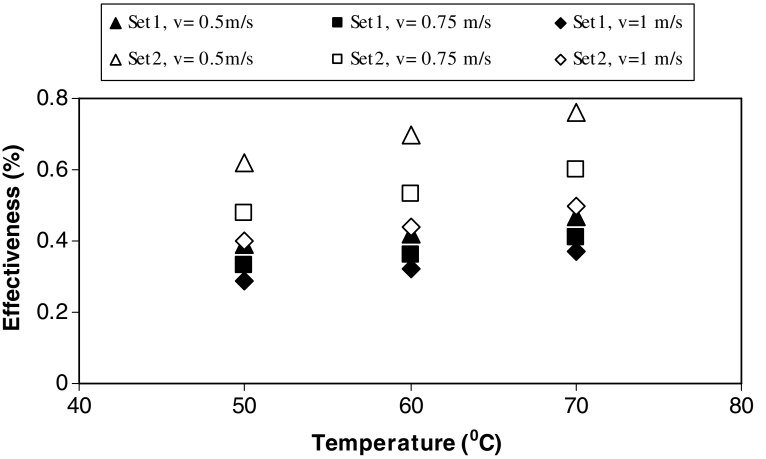

Fig. 7. Influences of temperature and velocity on effectiveness.

the hot-air inlet-velocity on the heat-transfer rate of the CLOHP/CV air-preheater. It can be seen that, when the hot-air inlet-velocity increases with temperature, the heat-transfer rate also rises. This is because, when the hot air inlet-velocity decreases with temperature, the air outlet-temperature also increases. Thus, the temperature difference between the inlet and the outlet air also increases and the actual heat-transfer rate will be high. It can be concluded that, if the hot-air inlet-velocity is lower at the highest temperature, then the heat-transfer rate increases.

6.4. Influence of velocity on the effectiveness

In this experiment, for the CLOHP/CV air-preheater having two sets, the hot-air velocities were 0.5, 0.75 and 1 m/s with temperatures 50, 60 and 70 °C. Fig. 7 shows the effect of the hot-air inlet-velocity on the effectiveness of the CLOHP/CV air-preheater. It can be seen that, when the hot-air inlet-velocity is lower with the temperature being the highest, the effectiveness also rises because the air outlet-temperature also increases. Thus, the temperature difference between the inlet and the outlet air also increases and the actual heat-transfer rate will be high. It can be concluded that if the hot-air inlet-velocity is lower with temperature being the highest, then the effectiveness also increases.

6.5. Relative humidity

In this experiment, for the CLOHP/CV air-preheater having two sets, the hot-air temperatures were 50, 60, and 70 °C with velocities 0.5, 0.75 and 1 m/s. The test result shows that the relative humidity of the air stream after passing through the condenser of the CLOHP/CV can be reduced to the range 54–72% from 89–100%, the trend of reducing relative humidity is in good agreement with Wu et al. [7], as shown in Fig. 8.

Table 2
The results of the experiments

T	Set	0.5 (m/s)			0.75 (m/s)			1 (m/s)			V (m/s)							ε		
		T_{hi}	T_{ci}	T_{co}	T_{hi}	T_{ci}	T_{co}	T_{hi}	T_{ci}	T_{co}	0.5			0.75		1		V (m/s)		
						(°C)					Q_{pred}	Q_{act}	Q_{max}	Q_{act}	Q_{max}	Q_{act}	Q_{max}	0.5	0.75	1
50	1	32	25	28	38	25	28	41	25	30	547	287	736	663	1992	965	3295	0.39	0.33	0.29
60		34	25	28	40	25	29	47	25	31	880	378	891	783	2184	1368	4300	0.42	0.36	0.32
70		37	25	29	42	25	30	49	25	33	1154	537	1133	977	2364	1635	4425	0.47	0.41	0.37
50	2	50	28	43	50	34	41	50	37	42	3041	3573	5726	2629	5513	2178	5496	0.62	0.48	0.40
60		60	29	51	60	38	49	60	44	51	3940	5125	7358	3838	7285	3064	7020	0.70	0.53	0.44
70		70	29	59	70	40	51	70	48	58	5745	7618	9618	5738	9587	4954	9187	0.76	0.60	0.50

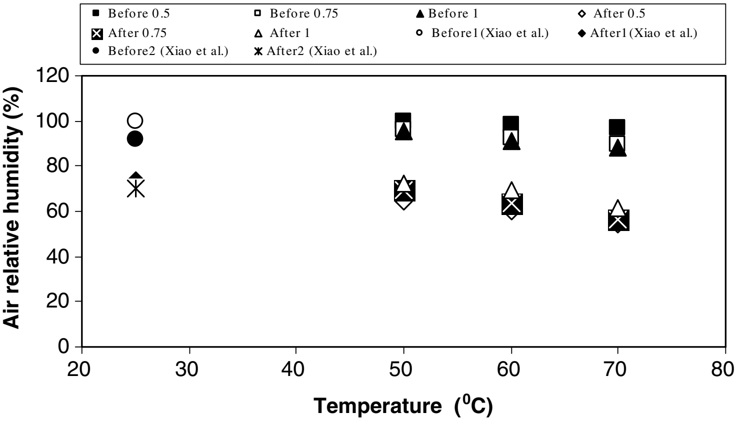

Fig. 8. Air relative humidity and temperature.

7. Conclusions

The aim of this paper is to design, construct, and test the CLOHP/CV air-preheater for reducing the relative humidity in drying systems and for recovering the waste heat from the drying cycle. It can be concluded that

- With an increase in hot-air temperature from 50 to 70 °C, the heat-transfer rate slightly increases.
- With an increase in hot-air temperature from 50 to 70 °C, the effectiveness slightly increases.
- With increases in the velocity from 0.5, 0.75 to 1 m/s, the heat-transfer rate slightly decreases.
- With increases in the velocity from 0.5, 0.75 to 1 m/s, the effectiveness slightly decreases.
- The relative humidity reduced to the range 54–72% from 89–100%.
- The CLOHP/CV air-preheater can reduce the relative humidity and achieve energy thrift.

Acknowledgements

This research has been supported generously by the Faculty of Engineering Mahasarakham University, Research Organization of Mahasarakham University, Thailand, and the Energy Policy & Planning Office (EPPO), Ministry of Energy, Thailand. The authors express their sincere appreciation for all of the support provided.

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