Closed-loop oscillating heat-pipe with check valves (CLOHP/CVs) air-preheater for reducing relative humidity in drying systems

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Accepted 9 September 2006
Available online 8 December 2006

Abstract

A CLOHP/CV air-preheater has been used for recovering the waste heat from the drying cycle. The CLOHP/CV heat-exchanger consisted of copper tubes 3.58 m long and internal diameter 0.002 m. The evaporator and condenser sections were 0.19 m long, the adiabatic sections 0.08 m long, the hot air velocity was 0.5, 0.75 or 1.0 m/s with the hot air temperature 50, 60 or 70 °C, and the relative humidity was 100%. The working fluid was R134a with a filling ratio of 50%. The hot-air temperature increased from 50 to 70 °C; the heat-transfer rate increased slightly. The velocity increase from 0.5 0.75, to 1.0 m/s led to the heat-transfer rate slightly decreasing. The velocity increase from 0.5 to 1 m/s led to a slight decrease in effectiveness. As the hot-air temperature increases from 50 to 70 °C, the effectiveness slightly increased; and the relative humidity was 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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0306-2619/$ - see front matter
doi:10.1016/j.apenergy.2006.09.009

Nomenclature

A	area (m^2)
Bo	bond number, $Di\left[g\left(\frac{\rho_l-\rho_v}{\sigma}\right)\right]^{\frac{1}{2}}(-)$
C_p	specific heat at constant pressure (J/kg.k)
C_v	number of check valve (-)
D	diameter (m)
Fr	Froude number, $\frac{Q_m^2}{\rho_v^2\ h_{fg}^2 Di^5 g}(-)$
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, $\left(\frac{q}{h_{fg}\rho v(\rho g(\rho l-\rho v)/\rho^2 v)^{1/4}}\right)(-)$
k	thermal conductivity (W/m K)
L	length (m)
Pr_v	Prandtl number of vapour $\left(\frac{C_{pv}\mu_v}{k_v}\right)(-)$
Q	heat-transfer rate (W)
q	heat flux (W/m^2)
R_{cv}	Ratio of check valves to number of the capillary tube (-)
RH	relative humidity (%)
T	temperature (°C)
V	velocity (m/s)
We	Weber number, $\frac{Q_m^2}{\rho_v h_{fg} Di^3 \sigma}(-)$
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	vapour

1. Introduction

The aim of the dryer is to reduce the moisture content of a product. Traditionally, the application of a heat-pipe air-preheater to the dryer is unable to use its waste heat. The application of a closed-looped oscillating heat-pipe with check valves (CLOHP/CVs) air-preheater for relative-humidity (RH) control in drying systems has 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: it has a simple structure and fast thermal-response [1,2]. The CLOHP/CV consists of a long capillary tube bent into many turns and the evaporator section, adiabatic section, and condenser sections are located at these turns, with the ends joined to form a closed loop. The system 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 the CHOHP/CV has a high-efficiency heat-transfer. Pipatpaiboon et al. [4] studied the effects of inclination angle, working fluid and number of check vales on the characteristics of the heat-transfer in a closed-looped oscillating heat-pipe with check valves. The CLOHP/CV equipped with 2 check valves, had the highest heat-transfer [4]. Pipatpaiboon [5] studied the correlation of heat-transfer of a closed-looped oscillating heat-pipe with the number of check valves (CLOHP/CV). Rittidech et al. [6] studied the closed-ended oscillating heat-pipe (CEOHP) air-preheater for achieving energy thrift in a dryer. Wu et al. [7] studied the application of heat-pipe exchangers for humidity control in air-conditioning systems. This type of heat exchanger can be an advantageous replacement for a conventional reheat-coil, resulting in energy savings and enhancing the cooling capability of the cooling coils with little or no external energy needed.

The use of a CLOHP/CV as an air pre-heater is widely accepted as a heat-transfer device for high heat-loads [1]. Nevertheless, improvements of the heat-pipe air-preheater for the dryer are needed. They should incorporate one or more direction-control one-way check values in the loop, so that the working fluid can circulate in the specified direction only in shown Fig. 1.

2. The check valve

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

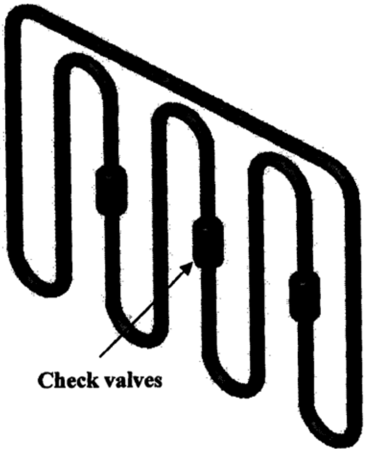

Fig. 1. Closed-loop oscillating heat-pipe with check valves (CLOHP/CVs).

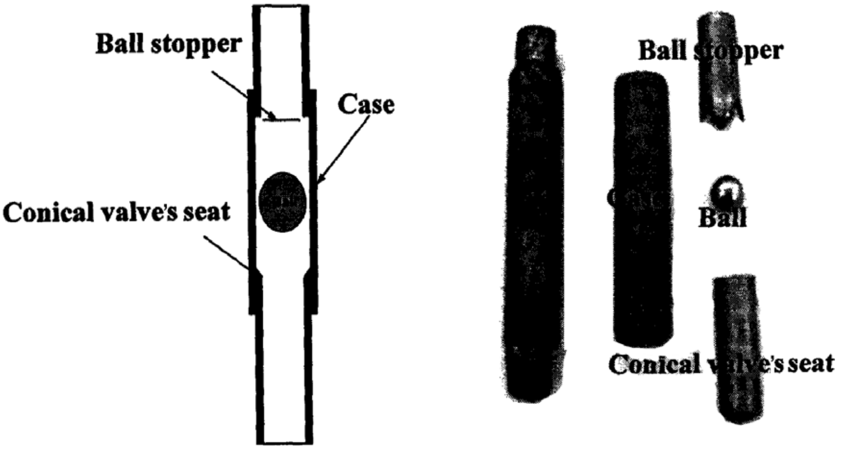

Fig. 2. The check valve.

3. The conventional drying-cycle

The basic principle of the drying process is that fresh air was heated (by an electric heater). Then the hot air moves though the product in the chamber. The heat is transferred to the product for reducing moisture as shown in Fig. 3.

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

The maximum heat-transfer rate, $Q_{\max}$, of the heat-pipe heat-exchanger for the drying system is

$$Q_{\max} = C_{\min}(T_{\mathrm{hi}} - T_{\mathrm{ci}}) \quad (1)$$

and

$$C_{\min} = \rho VAC_{\mathrm{p}}$$

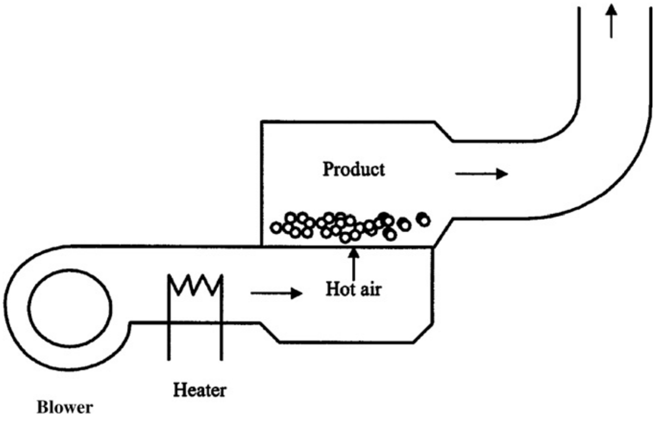

Fig. 3. The conventional drying cycle.

The inner diameter of the CLOHP/CV was calculated by Meazawa et al. [2] as

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

The type of working fluid that is appropriate for the operation temperatures was selected.

The working temperature for the drying system was chosen.

The heat-transfer rate ($Q_{\max}$) was calculated from the expressions for KU_{90}; L_e, L_c and L_t are specified for the duct size for the dryer.

The velocity is either 0.5, 0.75 or 1.0 m/s

The values of Bo, Fr_v, Ja, Pr, R_{cv}, We, ρ_v, ρ_1 and L_e/D_i are calculated and the heat flux of the CLOHP/CV air-preheater is determined by the correlation equation (3) taken from [5]. The standard deviation of this equation is ±30%.

$$Ku_{90} = 0.004\left[B0^{2.2} Fr^{1.42} Ja^{1.2} Pr^{1.02}\left[\frac{\rho v}{\rho l}\right]^{0.98} R_{cv}^{1.4} We^{0.8}\left[\frac{L_e}{D_i}\right]^{0.5}\right]^{0.107} \tag{3}$$

The heat-transfer rate, Q_{90}, for the vertical heat-pipe is calculated from Ku_{90}, and translated to the heat flux (q) via

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

KU_{90} indicates the ratio of heat flux through the CLOHP/CV to the critical heat-flux of the working fluid. It shows whether the obtained heat fluxes of a CLOHP/CV exceeds than the critical heat-flux of the working fluid or not, i.e. whether or not there is pool boiling of the working liquid in the evaporator section of the CLOHP/CV. Bo indicates the ratio of buoyancy force to surface tension force of the working fluid. If $Bo > 1$, nucleate boiling occurs in the heat pipe. Fr, i.e. the inertial force divided by gravitational force, is used in momentum transfer in general, and open-channel flow and wave and surface behaviour calculations in particular. Ja is the latent heat divided by the specific heat at constant pressure. Pr indicates the ratio of momentum diffusivity to the thermal diffusivity of the vapour slug. If its value is very low, the vapour slug will be able to transfer the thermal energy to the condenser section relatively efficiently. Therefore, the value of Ku_{90} or heat flux will be high. The vapour-phase density to the liquid-phase density (ρ_v/ρ_l) of the working fluid dictates the working pressure of the working fluid within the CEOHP. R_{cv} indicates the number of check valves to the number of turns of the CLOHP/CV. We is the ratio of the inertial force to the surface-tension force. L_e/D_i defines the size of the CLOHP/CV. For example, if the value of L_e/D_i is very high, then the tube would be large and the evaporator section would 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 is 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 value of KU_{90} or heat flux will be low.

Values of some of these parameters are shown in Table 1.

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

Table 1
Physical parameters of the CLOHP/CV air-preheater

Physical parameters	Description (Set 1)	Description (Set 2)
Material of tube	Copper	Copper
Inner diameter	0.002 m	0.002 m
Dimensions 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/Set	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 from correlation [4]	1216.38 W	3040.95 W

5. Experimental set-up

5.1. Prototype

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

5.2. Test rig

The CLOHP/CV prototype was installed in a test rig, as shown in Fig. 5. The hot air coming from the heater flows through the air-preheater. The initial and final temperatures

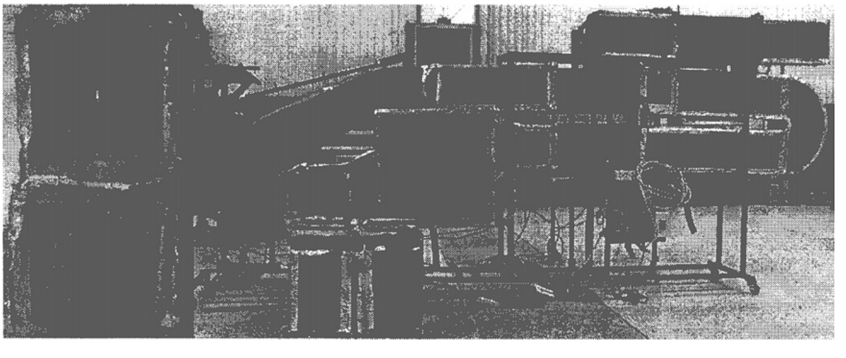

Fig. 4. The prototype CLOHP/CV air-preheater.

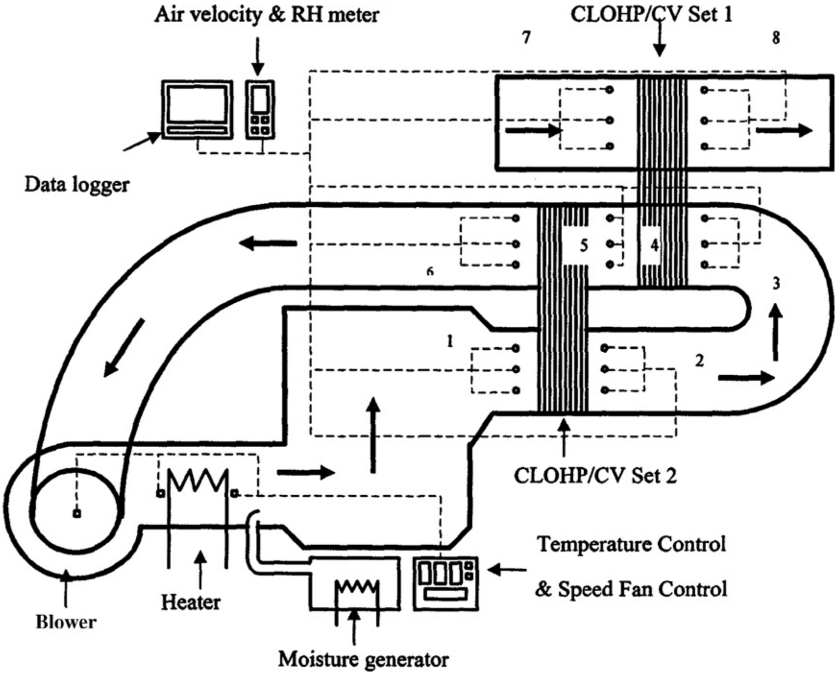

Fig. 5. Test rig: 1, T_{hi}; 2, T_{ho}; 3, T_{hi}; 4, T_{ho}; 5, T_{ci}; 6, T_{co}; 7, T_{ci}; 8, T_{co}.

are measured with 12 type-K thermocouples installed on the evaporator section and 12 more on the condenser. These thermocouples were connected 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 the heat-transfer rate

The experimental results present the effect of the hot-air temperature on the heat-transfer rate in Fig. 6. These figures are compared with the experimental results and the predictions from the correlation [5]. It can be seen that, when the hot-air inlet temperature increases with velocity, the heat-transfer rate also rises. This is because, when the hot-air inlet-temperature increases, the air outlet-temperature also increases. Thus, the temperature difference between the inlet and outlet air temperature also increases and the actual heat-transfer rate will be high. The measured heat-transfer rate was lower than that predicted via the correlation [5]. However, the predictions compare well with 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 the heat-transfer rate increases.

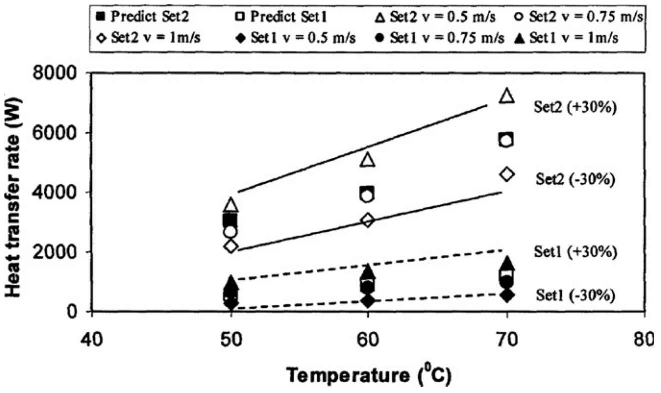

Fig. 6. Effects of hot-air temperature on heat-transfer rate.

6.2. *Effect of hot-air temperature on thermal effectiveness*

Fig. 7 shows the effect of the hot-air inlet-temperature on the effectiveness of the CLOHP/CV air-preheater. When the hot air inlet-temperature increases, the effectiveness also rises because the air outlet temperature also increases. Thus, the temperature difference between the inlet and 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, the effectiveness increases as shown in Table 2.

6.3. *Effect of velocity on the heat-transfer rate*

Fig. 6 shows the effect of 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 the highest temperature, the heat-transfer rate also rises. Thus, the temperature difference between the inlet and outlet air also increases and the actual heat-transfer rate will be high.

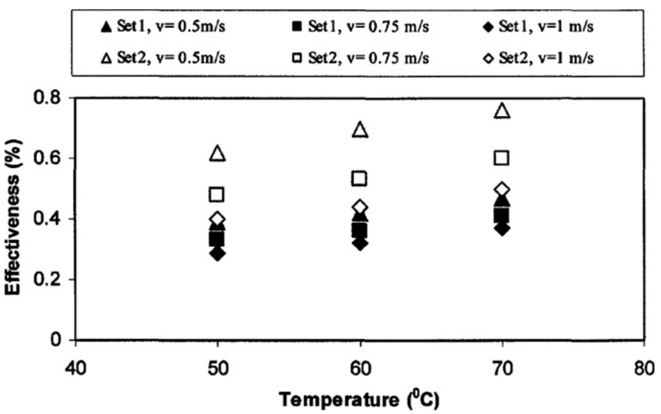

Fig. 7. Effects of temperature and velocity on effectiveness.

Table 2
The results of the experiment

T	Set	0.5 (m/s)			0.75 (m/s)			1.0 (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		1.0		V (m/s)		
						(°C)					Q_{prod}	Q_{act}	Q_{max}	Q_{act}	Q_{max}	Q_{act}	Q_{max}	0.5	0.75	1.0
50		32	25	28	38	25	28	41	25	30	547	287	736	663	1992	965	3295	0.39	0.33	0.29
60	1	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		50	28	43	50	34	41	50	37	42	3041	3573	5726	2629	5513	2178	5496	0.62	0.48	0.40
60	2	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

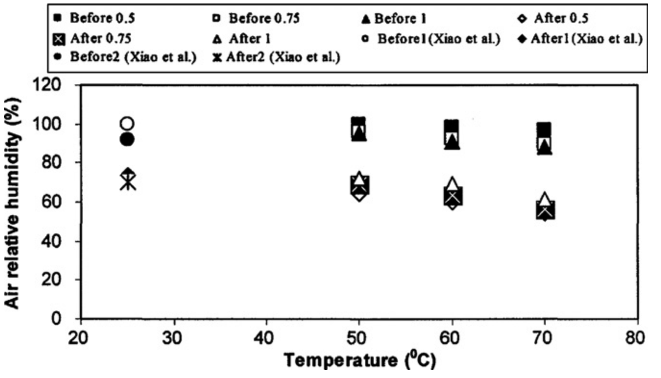

Fig. 8. Air relative humidity versus temperature.

6.4. *Effect of velocity on the effectiveness*

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, the effectiveness rises because the air outlet temperature also increases. Thus, the temperature difference between the inlet and outlet air also increases and the actual heat-transfer rate will be high.

6.5. *Relative humidity*

The test results show 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 the reducing relative humidity is in good agreement with Xiao et al. [7], as shown in Fig. 8.

7. Conclusions

This paper describes a CLOHP/CV air-preheater for achieving a reduced relative-humidity in drying systems and for recovering the waste heat from the drying cycle. It can be concluded that:

- As the hot-air temperature increases from 50 to 70 °C, both the heat-transfer rate and effectiveness slightly increase.
- As the velocity increases from 0.5 to 1.0 m/s, both the heat-transfer rate and the effectiveness slightly decrease.
- The relative humidity was reduced from 89 to 100% to the range 54 to 72%
- The CLOHP/CV air-preheater can reduce relative humidity and achieve energy thrift.

Acknowledgement

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

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