

Design and construction of an oven for drying palm bunch using glycerin as fuel together with using closed-loop oscillating heat-pipe with check valves (CLOHP/CV) heat exchanger for waste heat recovery

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This research addresses design and construction of an oven (2 m x 3 m x 2 m) for effectively drying palm bunch using glycerin as a fuel and a closed-loop oscillating heat-pipe with check valves (CLOHP/CV) as a heat exchanger for waste heat recovery. In each experiment, palm bunches (500 kg) were baked in oven with and without CLOHP/CV heat exchanger. CLOHP/CV (0.2 m x 0.8 m x 0.5 m) is made of copper tubes (inner diam, 2.03 mm). Working fluids were distilled water, ethanol and R134a. Waste heat from oven was recovered by heat exchanger and was beneficial for pre-heating the air in combustion process. Pre-heating was useful in burning glycerine, and distribution of heat inside oven with CLOHP/CV was better than without CLOHP/CV. Consequently, palm bunches received uniform heat that restrained enzyme thus slowing dissolution reactions that would otherwise produce free fatty acids and cause loss of palm oil. Use of a CLOHP/CV also reduced moisture content of palm bunches to 1.2 wt% on dry basis. When using oven with CLOHP/CV as a heat exchanger with R134a as working fluid, the highest thermal efficiency of drying palm bunch was 42.4%, highest effectiveness of CLOHP/CV was 43.0% and highest efficiency of glycerin stove was 45.0%.

Keywords: Closed-loop oscillating heat-pipe, Glycerin, Palm bunch oven

Introduction

Biodiesel can come from palm fruit, which is baked and compressed to release its oil. A palm bunch oven is essential in oil extraction process and is appropriate for developing a design change primarily because fresh palm fruit baking inhibits enzyme, which stops disintegration reaction of fatty acid causing a loss of oil. During baking process, heat leaves oven from smokestack; thus requiring a heat exchanger that can transfer heat from latent heat of a working fluid within the pipes, which will evaporate when it obtains heat from heat source, transfer heat to complete cooling, then condense and return to evaporator section again. A closed-loop oscillating heat-pipe with check valves (CLOHP/CV) can be installed as a heat exchanger^{1,2}, which has high effectiveness^{3,4}, and can be used for heat exchange of chimney smoke by pulling out hot air to mix with a glycerin fuel in a combustion chamber that allows for improved disintegration of glycerin fuel and increased temperature

distribution⁵. Biodiesel fuel producers treat glycerin as a waste product.

This study presents joining a CLOHP/CV and glycerin into a baking oven with palm oil fruit bunch, and ultimately uses it to improve systems' energy profile. Also, a comparison is presented between a palm bunch oven with and without CLOHP/CV.

Experimental Section

One unit processed 500 kg of palm bunch in the oven for 90 min. Test unit used water, ethanol and R134a as working fluids. Experimental apparatus (Fig. 1a) consists of an outside oven and temperature reading points (Fig. 1b) monitored inside thermal distribution after installing CLOHP/CV and glycerin burner. Thermocouples (Yokogawa DX200 with $\pm 0.1^\circ\text{C}$ accuracy, 20 channel input and -200°C to 1100°C temperature-range) were installed inside oven (16), at CLOHP/CV (13) and at glycerin burner (2). Type K thermocouples (OMEGA with $\pm 0.1^\circ\text{C}$ accuracy) measured wind speed at three points each at inlet evaporator section and at outlet condenser section. Air

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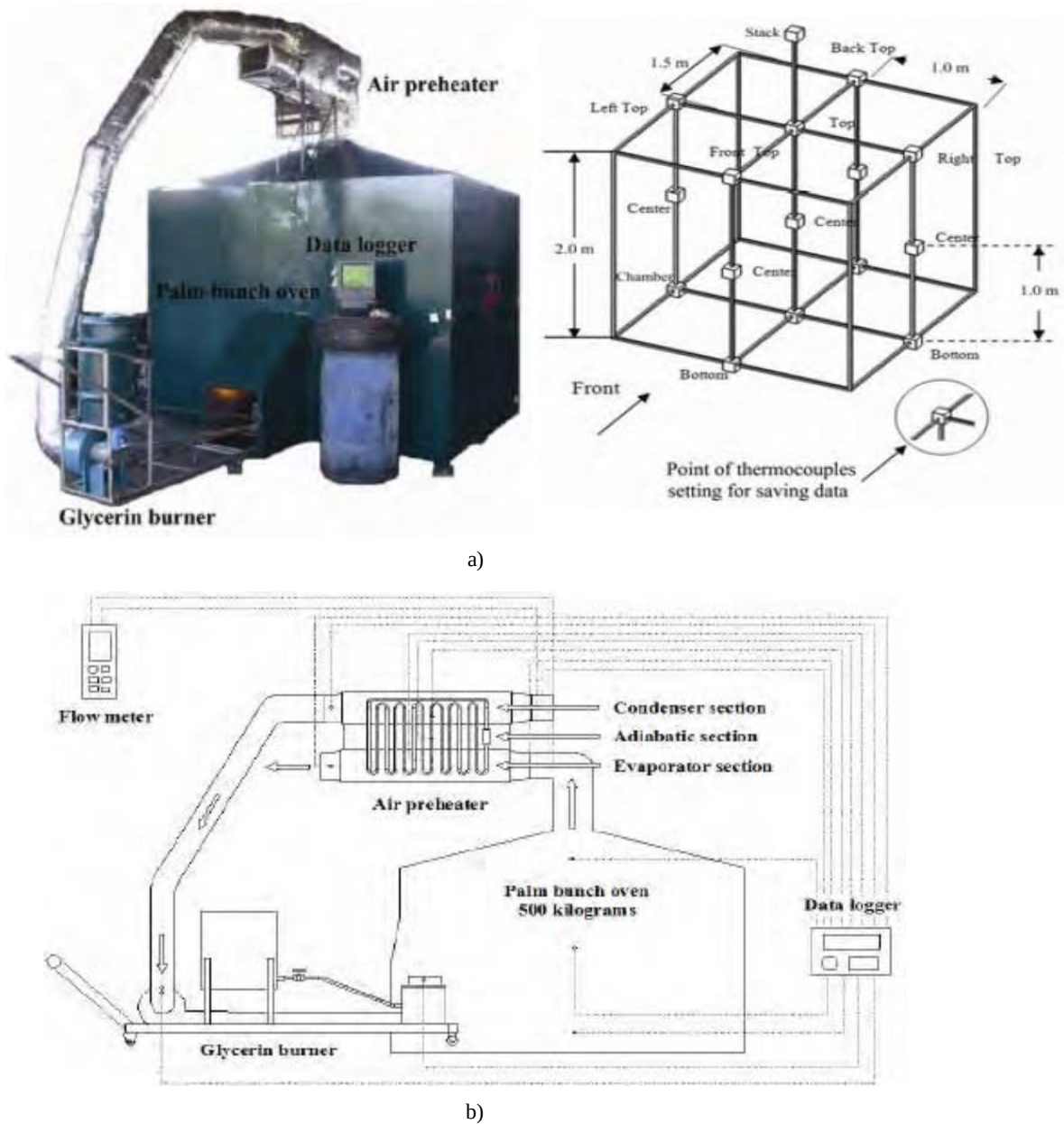


Fig. 1—Design of palm bunch oven: a) Experimental apparatus; b) Schematic diagram of experimental procedure

tubes (Testo 445 types) and pilot tube (accuracy ± 0.05) measured from 0 to 100 m/s. Weight was measured by an analogical scale with ± 10 g of uncertainty.

Palm Bunch Oven

Palm bunch oven (size, 2 m x 3 m x 2 m; age, 4 y; wt, 10-15 kg a bunch) was obtained from farmers in Kut Bak district Sakon Nakhon Province, Thailand. Palm was obtained from strain Camera Partnership (Tenera), which is a high weight palm that has many thick shells, giving more oil.

Thermal Efficiency Analysis of Palm Bunch Oven

Thermal efficiency of palm bunch oven is calculated as

$$h_{th} = \left(\frac{Q_{\text{Glycerine}} - Q_{\text{Loss}} - Q_{\text{Stack}}}{Q_{\text{Glycerine}}} \right) \times 100\% \quad \dots(1)$$

$$Q_{\text{Glycerine}} = \dot{m}HHV \quad \dots(2)$$

$$Q_{\text{Loss}} = Q_{\text{Convection}} = Ah_m(T_s - T_\infty) \quad \dots(3)$$

where, h_{th} = thermal efficiency of palm bunch oven (%), $Q_{\text{Glycerine}}$ = heat of glycerin fuel (W), Q_{Stack} = heat-transfer rate at stack (W), Q_{Loss} = heat loss of palm bunch oven (W), $\dot{m}$ = mass flow rate of glycerin fuel (kg/s), HHV = higher heating value (MJ/kg). $Q_{\text{Convection}}$ = heat convection (W), A = area (m^2), h_m = coefficient of convective heat, T_s = wall temperature, T_∞ = ambient temperature.

Characteristic length of oven geometry is calculated as $h_m = f(\text{Pr}, \text{Nu}_m, \text{Ra}_L, \text{Gr}_L)$. Prandtl number (Pr) is derived from air properties based on $T_f = (T_w + T_\infty)/2$ where T_w is average temperature from four walls. Grashof Number (Gr) is calculated as

$$\text{Gr}_L = \frac{gb(T_w - T_\infty)L^3}{\nu^2} \quad \dots(4)$$

where g is gravitational acceleration (9.81 m/s^2), b is volumetric thermal expansion, which is different than T_f that is $1/T_f = b$, n is a constant depending on air properties, and L is characteristic length. Rayleigh number (Ra_L) is related to Pr and Gr_L as $\text{Ra}_L = \text{Gr}_L \text{Pr}$.

For heat transfer at a boundary surface within a fluid, Nusselt number (Nu) is the ratio of convective to conductive heat transfer across (normal to) the boundary. Appropriate correlation is

$$\text{Nu}_L = \left[0.825 + \frac{0.387 \text{Ra}_L^{1/6}}{\left(1 + \left(\frac{0.492}{\text{Pr}} \right)^{9/16} \right)^{8/27}} \right]^2 \quad \dots(5)$$

The h_m is obtained as $h_m = \frac{k \text{Nu}_m}{L}$, where k = thermal conductivity of air and L is characteristic length. Q_{Loss} is calculated in terms of $Q_{\text{Convection}}$, when it has heat and smoke.

Design of CLOHP/CV Heat Exchanger

CLOHP/CV heat exchanger is made of a copper capillary tube bent into 40 meandering turns and filled with water, ethanol and R134a at a filling ratio of 50% of the tube's volume. It is made up of three sections [evaporator (L_e), adiabatic (L_a), and condenser (L_c)], with

two check-valves set up along CLOHP/CV. Maximum inner diameter of CLOHP/CV should be considered in order to take waste heat from the stack of oven to be reused, and then find heat transfer value, which could be done in theory design. As an initial step, working fluid in heat pipe is selected based on waste temperature phase of stack. Then diameter of CLOHP/CV is calculated

as⁶ $D_{\text{max}} \leq 2 \sqrt{\frac{s}{r_l g}}$, where D_{max} is maximum inner diameter of capillary tube (m), s is surface tension of fluid (N/m), r_l is density of fluid (kg/m^3). Next, length of L_e (150 mm), L_a (80 mm) and L_c (150 mm) is selected, followed by values are set to find heat transfer rate. Standard deviation (30%) is calculated as⁷

$$\text{Ku}_{90} = \frac{q}{r_v h_{fg} \left[s \cdot g \left(\frac{r_l - r_v}{r_v^2} \right) \right]^{\frac{1}{4}}} \quad \dots(6)$$

$$\text{Ku}_{90} = 0.0004 \left[\text{Bo}^{2.2} \text{Fr}^{1.42} \text{Ja}^{1.2} \text{Pr}^{1.02} \left[\frac{r_v}{r_l} \right]^{0.98} \text{Rcv}^{1.4} \text{We}^{0.8} \left[\frac{Le}{Di} \right]^{0.5} \right]^{0.138} \quad \dots(7)$$

Heat transfer rate (Q , W) is calculated by Ku_{90} , and heat flux (q , W/m^2) is given as $Q = (qA)$. Performance of a CLOHP/CV is represented by its effectiveness ($e = Q_{\text{actual}}/Q_{\text{max}}$), which is the ratio of heat transfer rate of a CLOHP/CV (Q_{actual}) to maximum possible heat transfer rate (Q_{max}). Ku_{90} indicates the ratio of heat flux of CLOHP/CV to critical heat flux of working fluid. It shows whether obtained heat fluxes of CLOHP/CV are more than critical heat flux of working fluid or not, and if there is the pool boiling phenomena of a working fluid in evaporator section of a CLOHP/CV. Bond number (Bo) indicates the ratio of buoyancy force to surface tension force of working fluid. If $\text{Bo} > 1$, it means that nucleate boiling occurs in heat pipe. Froude number (Fr) indicates the ratio referring to inertial force/gravitational force, and it is used in momentum transfer in general and open channel flow and wave and surface behavior calculations in particular. Jakob number (Ja) indicates the ratio and refers to (latent heat/specific heat at constant pressure). Prandtl number (Pr) indicates the ratio of momentum diffusivity to thermal diffusivity of

vapor slug. If the value is very low, vapor slug will be able to transfer thermal energy to condenser section relatively efficiently. Therefore, value of Ku_{90} or heat flux will be high. (r_v / r_l) indicates vapor phase density to liquid phase density of working fluid that represents working pressure of working fluid within CEOHP.

The ratio of check valves (R_{cv}) is that of the capillary tubes, which connects evaporator and condenser sections of a CLOHP/CV, and represents the ratio of check valves to the number of turns on a CLOHP/CV. Check valves, which consisted of four sections (ball, case, ball stopper, and conical valve seat), controls liquid slug flow in one direction. Ball is made to control flow direction, and inserted in the middle of all compounds. Ball stopper stops movement of the ball.

Weber number (We) indicates the ratio and refers to inertial force/surface tension force, and is used in momentum transfer in general and bubble droplet formation and breakage of liquid jets calculations in particular. (L_e/D_i) defines size of CLOHP/CV. If the value of (L_e/D_i) is very high, then tube would be large and evaporator section would be short. Due to 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 tube would be small and evaporator section would be long. Because the boiling phenomenon within this type of tube will be akin to boiling phenomenon in a confined channel, the value of Ku_{90} or heat flux will be low.

Glycerin Burner

Glycerin burner (0.5 m x 2.2 m x 1 m) consisted of a blower (1/3 hp), an air tube (diam, 10 cm), and a fuel tube (diam, 2.5 cm). Glycerin used was derived from a chemical sulfuric acid separation process. The 1:10 ratio of total glycerin was left for 1 min, and used as fuel (HHV, 22,562.2 kJ/kg). Incomplete combustion of glycerin can cause toxic gas (Acrolein). For complete glycerin combustion, air combined burning is used. In designing a glycerin oven, there must be sufficient air volume because actual air per fuel is higher than the air ratio of the theory – sometimes referred to as excess air. The amount of excess air used for fuel combustion mixed with glycerin in a heating oven with palm bunch oven is 16.16 kg/kg_{fuel}. To raise combustion efficiency of glycerin, hot air coming from heat exchanger in CLOHP/CV is mixed with glycerin.

Results and Discussion

Temperature Distribution

Effect of temperature distribution is shown with time of palm bunch oven without (Fig. 2a) and with CLOHP/CV heat exchanger when using water (Fig. 2b), ethanol (Fig. 2c) and R134a (Fig. 2d) as working fluid. CLOHP/CV gave a steadier temperature than when operating without CLOHP/CV. It also affected palm bunches by providing uniform heat that restrained enzyme lipase, which causes free fatty acids (FFAs) and glycerol, affecting quality of palm oil. Steady heat would officiate to inhibit lipase, thus delaying dissolution reactions, which would otherwise produce FFAs and cause palm oil reduction. Using CLOHP/CV as a heat exchanger also reduced moisture content of palm bunches (dry basis) from 19.0 wt% to 1.2 wt% (Fig. 3).

Thermal Efficiency

Thermal efficiency of palm bunch oven was found as follows: original oven, 32.0; with CLOHP/CV using water, 35.3; with CLOHP/CV using ethanol, 37.0; and with CLOHP/CV using R134a, 42.4%. In every operation, installation of working fluids improved thermal efficiency over original oven. Palm bunch oven with CLOHP/CV using R134a gave maximum thermal efficiency of 42.4% which was better than other oven types. Installation of CLOHP/CV was helpful in temperature distribution because R134a had the lowest latent heat of vaporization, which made working fluid boil rapidly and transfer heat to condenser section of heat pipe. In addition, installation of CLOHP/CV improved temperature distribution because heat provided to palm bunch oven was from the combustion of glycerin. Waste heat from oven was recovered by heat exchanger and was beneficial for pre-heating the air in combustion process. Pre-heating was useful for burning glycerin.

CLOHP/CV Effectiveness

When using R134a as working fluid, not only was the maximum effectiveness 43.0% (Fig. 4), which allowed working fluid to boil rapidly, but additionally, heat transferred rapidly to heat pipe's condenser section. The heat had a higher temperature with R134a than with water and ethanol as working fluids. Hot air, which had already obtained a high temperature before the burning reaction with glycerin fuel, assisted glycerin fuel dispersion so that the burning process was perfect.

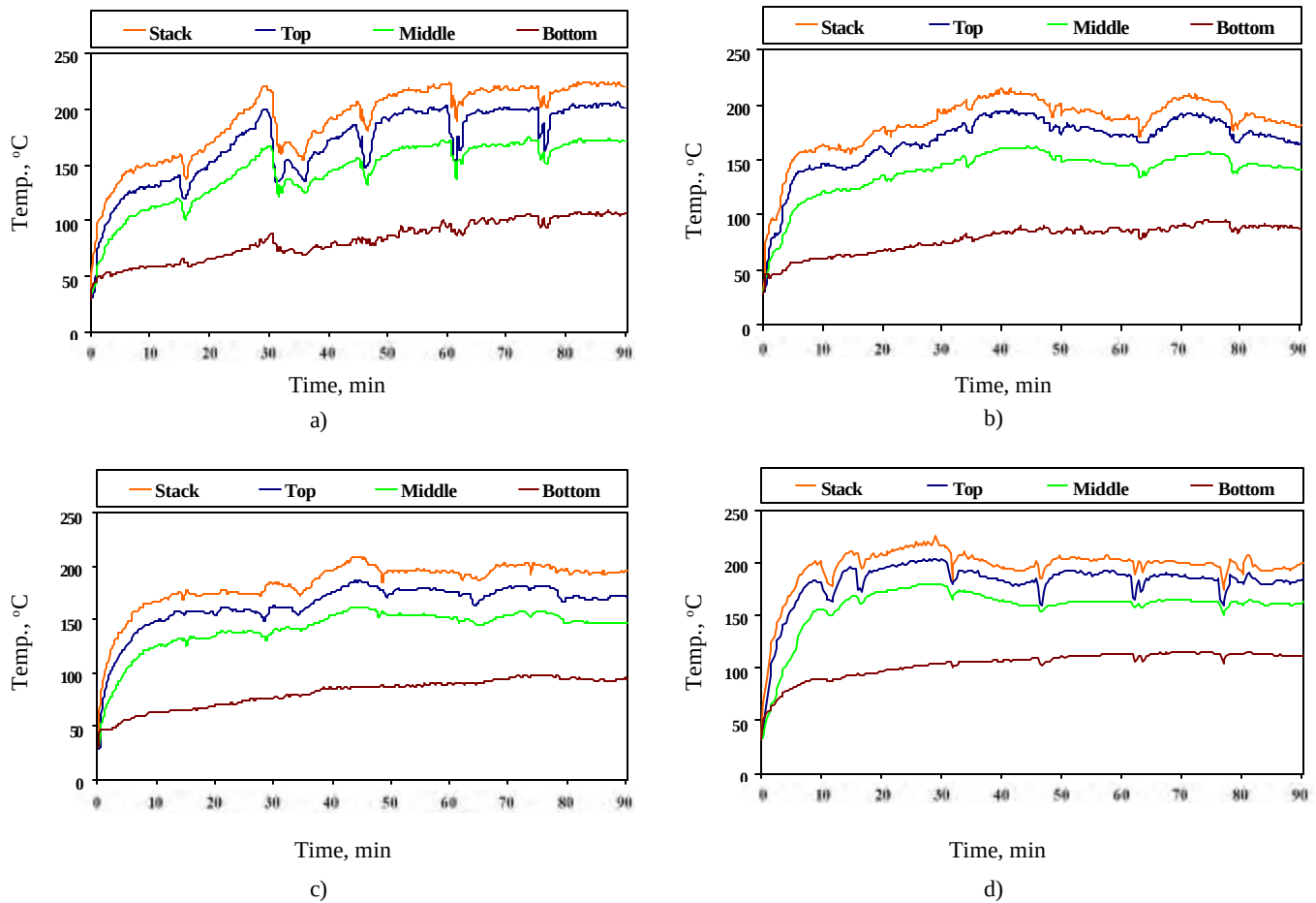


Fig. 2—Effect of temperature distribution of palm bunch oven: a) without CLOHP/CV heat exchanger; b) with CLOHP/CV heat exchanger when using water as working fluid; c) with CLOHP/CV heat exchanger when using ethanol as working fluid; and d) with CLOHP/CV heat exchanger when using R134a as working fluid

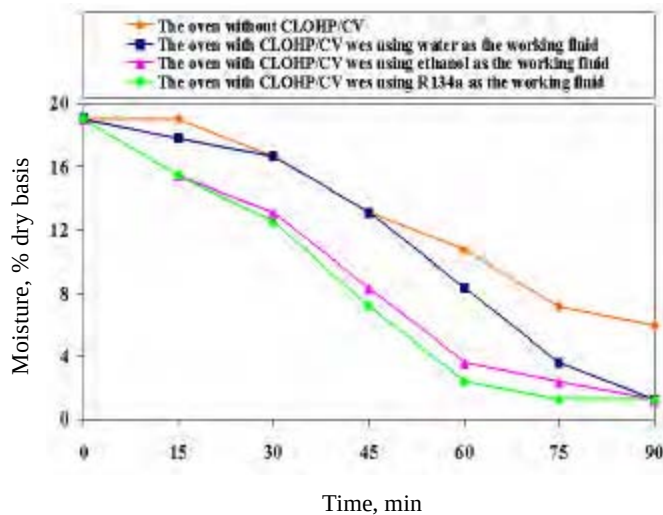


Fig. 3—Effect of palm bunch oven with CLOHP/CV heat exchanger on moisture content of palm bunch

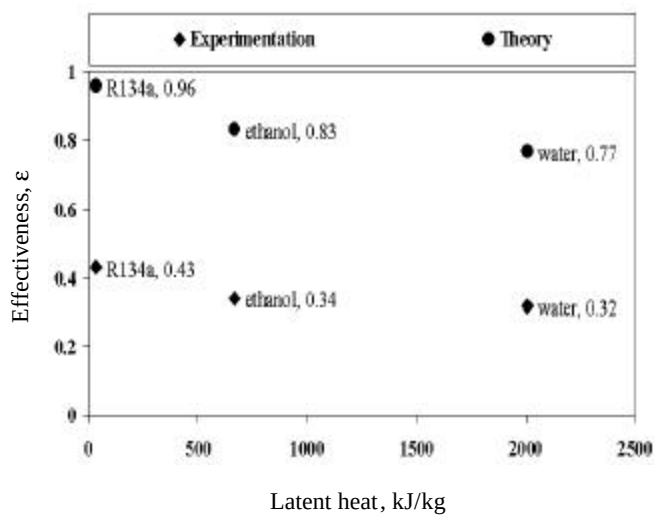


Fig. 4—Relationship between CLOHP/CV effectiveness and latent heat

Glycerine Burner Efficiency

Thermal efficiency of glycerine burner was found as follows: original glycerine burner, 32.0; glycerine burner with CLOHP/CV using water, 35.9; glycerine burner with CLOHP/CV using ethanol, 36.8; and glycerine burner with CLOHP/CV using R134a, 45.0%. Heat from hot air caused glycerin fuel to disperse reducing the stickiness, resulting improved burning. Maximum efficiency value of glycerin burner that used R134a was 45.0%, while oven without CLOHP/CV glycerin burner had an efficiency value of 32.0%.

Conclusions

A comparison between palm bunch oven with and without a CLOHP/CV showed that a CLOHP/CV serving as a heat exchanger helped thermal distribution in oven to be steadier than without CLOHP/CV. The CLOHP/CV using R134a was the most suitable configuration and yielded a moisture content of 1.2 wt% on dry basis. Thermal efficiency of palm bunch oven without a CLOHP/CV was 32%. In contrast, palm bunch oven with a CLOHP/CV using R134a had maximum thermal efficiency of 42.4%. Thus, installation was helpful to thermal distribution and improvement of thermal efficiency. Effectiveness of CLOHP/CV was maximum (43%) by using R134a as working fluid because R134a has low latent heat of vaporization and causes rapid heat transfer to condenser section. R134a transferred heat more efficiently than water or ethanol, and thus it was suitable for this baking process. With

respect to the efficiency of glycerin burner with CLOHP/CV, efficiency was 45.0% because glycerin fuel obtained heat from hot air, which positively affected glycerin fuel disintegration, resulting in a higher temperature and increased burning capability.

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