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A Small Size Essential Oil Refiner Using an Oscillating Heat Pipe for Essential Oil Condensation

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Abstract

This research investigated the design and building of a small size essential oil refiner using an oscillating heat pipe for essential oil condensation. Three condenser suit types were used: 1) condensation using water circulation, 2) condensation using a closed-end oscillating heat pipe (CEOHP) and 3) closed-loop oscillating heat pipe with check-valves (CLOHP/CV). CEOHP and CLOHP/CV were made from copper tubes with an inner diameter of 2 mm. R123 was used as the working fluid. The temperature of vapor for testing was 100, 110 and 120 °C. The vapor pressure for testing was 1, 1.5 and 2 bars.

Keywords: Heat pipe, oscillating heat pipe, OHP, essential oil refiner

Nomenclatures:

A	surface area of tube (m^2)
B_O	Bond number ($= d[g(\rho_l-\rho_v)/\sigma]^{1/2}$)
C_p	specific heat capacity constant pressure (J/kg·°C)
D,d	diameter (m)
Fr	Froude number ($= V^2/gd$)
g	gravitational acceleration (m/s^2)
h_{fg}	latent heat of vaporization (kJ/kg)
Ja	Jacob number ($= h_{fg}/(C_{p,l}T_v)$)
Ku	Kutateladze number ($= q/[h_{fg}\rho_v(\sigma g(\rho_l-\rho_v)/\rho_v^2)^{1/4}]$)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of turns
Pr_v	Prandtl number ($= C_{Pv}\mu_v/k_v$)
Q	heat transfer rate (W)
q	heat flux (W/m^2)
R_{CV}	ratio of check-valves
V	velocity (m/s)
We	Weber number ($= V^2\rho d/\sigma$)
t	thickness (m)
T	temperature (°C)

Greek symbols

k	thermal conductivity (W/m·K)
μ	viscosity (Pa·s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

e	evaporator
l	liquid
i	inside
o	outside
t	total
v	vapor
in	inlet
out	outlet

Introduction

Essential oil can be extracted from many plant parts. The demand for aroma oil in the market is quite significant due to its qualities and usefulness. Essential oils can be extracted using a variety of methods, although some are not commonly used today. Currently, the most popular method for extraction is steam distillation. Steam distillation to extract the essential oil requires that the plant material is placed into a still (very similar to a pressure cooker) where pressurized steam passes through the plant material. The heat from the steam causes globules of oil in the plant to burst and the oil then evaporates. The essential oil vapor and the steam then pass out of the top of the still into a water cooled pipe where the vapors are condensed back to liquids. At this point, the essential oil separates from the water and floats to the top.

A normal essential oil refiner is very large, difficult to move and costly, leading to significant research on essential oils [1-3]. In Thailand, researchers have studied the design and building of essential oil refiners. For example, Sajjavatee and Kadking [4] studied the design and building of a water and steam distillatory for essential oils from herbs or medicinal plants distilled at atmospheric pressure for the laboratory scale. Magkong and Yamsiri [5] designed an essential oil distiller consisting of 3 main components namely a still (still capacity as 95 liters), condenser and separator. The holding capacity of water was 20 liters and the raw (plant) material capacity was 10 - 13 kg/one operation. The condenser included 3 straight pipes, with a total length of pipe of 6 m, a water holding capacity of 320 L, but no cooling system.

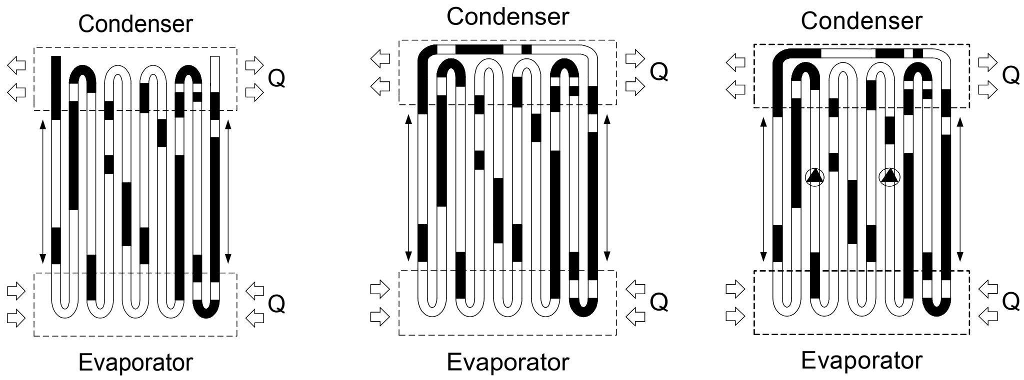


Figure 1 Types of oscillating heat pipe: (a) Closed-end oscillating heat pipe (CEOHP), (b) Closed-loop oscillating heat pipe (CLOHP) and (c) Closed-loop oscillating heat pipe with check valves (CLOHP/CV).

A heat pipe is a simple heat exchanger for heat transfer from 2 different temperature sources. There are many types of heat pipe, including the oscillating heat pipe (OHP) [6]. It is a new type of heat pipe, improved from a thermosyphon. It is also called a pulsating heat pipe. The oscillation of slugs and plugs in the OHP are self-sustained by the evaporation of liquid slugs and the condensation of vapour plugs. Therefore, the heat from the high temperature section can be transported to another section at lower temperature. The advantages of the OHP include simplicity of construction, only one tube, no capillary structure, high thermal performance, capability of operation in any position, and operational flexibility. Normally, OHP is made from capillary tubes with 3 basic types: closed end oscillating heat pipe (CEOHP), closed-loop oscillating heat pipe (CLOHP) and closed-loop oscillating heat pipe with check valves (CLOHP/CV). In all cases the OHP has 3 sections consisting of an evaporator, adiabatic and condenser sections [3]. Moreover, the OHP can transfer heat from the hot side to cold side at any inclination angle from the horizontal. CEOHP is very simply constructed but CLOHP/CV has the highness performance of all OHP. Heat transfer of OHP has been studied by many researchers [6-8]. As a result of the advantages of OHP, it has been used by many researches such as in 2006, the CLOHP/CV air-preheated by Meena [9]. The CLOHP/CV air-preheater can reduce the relative humidity and achieve energy thrift. In Meena's research [9], the velocity increased from 0.5 to 1 m/s leading 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 to 72 % from 89 to 100 %. Moreover, OHP can be used to transfer heat in any problem [4,5,10-16]. Thus, in 2013 Wannapakhe [17] studied the application of closed-end oscillating heat pipe for essential oil condensation. The CEOHP heat exchanger was added to the condenser of an essential oil refiner. It was found that the essential oil quantity was increased when the CEOHP heat exchanger was used working with condensation by water circulation. As a result of the advantages of CEOHP and CLOHP/CV, in this research the CEOHP and CLOHP/CV were used to improve the condensation part of a normal essential oil refiner, something that has never previously been reported.

Materials and methods

Experimental setup and procedure

CEOHP and CLOHP/CV refiner's condensers

The CEOHP and CLOHP/CV were made from copper capillary tube with an inner diameter of 2 mm. The inner diameter of the tube can be calculated by Eq. (1) [18].

$$d_{\max} < 2\sqrt{\frac{\sigma}{\rho_l g}} \tag{1}$$

where $d_{\max}$ is the maximum inner of capillary tube (m), σ is surface tension of fluid (N/m). ρ_l is density of fluid as a liquid (kg/m^3) and g is acceleration of gravity (9.81 m/s^2). The CLOHP/CV had one check-valve with the set-up shown in **Figure 2**. The best ratio of the number of check valves to number of turns was 0.2 (the number of check valve is 1; the number of turns is 20) [8,19].

The type of working fluid that is appropriate at the operational temperatures employed was R123 with a filling ratio of 50 % of the total volume of the tube. The evaporator, adiabatic and condenser lengths and number of turns were defined corresponding to the heat flux of the CEOHP refiner's condenser; it was solved using the correlation from Eq. (2) [8,15,19]. The Kutateladze number (Ku) of CEOHP and CLOHP/CV were defined in Eqs. (3) and (4), respectively. The standard deviation of Eqs. (3) and (4) are ±30 %.

$$q = Ku \times h_{fg}\rho_v(\rho_g(\rho_l - \rho_v)/\rho_v^2)^{1/4} \tag{2}$$

$$Ku_0 = 0.0052\left[\left(\frac{D_i^{4.3}L_t^{0.1}}{L_e^{4.4}}\right)n^{0.5}\left(\frac{\rho_v}{\rho_l}\right)^{-0.2}Pr_v^{-25}\right]^{0.116} \tag{3}$$

where Ku_0 is the ratio of heat flux to critical heat flux for the horizontal orientation. The D_i is the inner diameter of the tube (m), L_t is the total tube length (m) and L_e is the evaporator length. The number n is the number of turns in the CEOHP. ρ_v / ρ_l is the vapor phase to liquid phase density of the working fluid, Pr_v is the ratio of momentum diffusivity to the thermal diffusivity of the vapor slug.

For CLOHP/CV design in this research, the equation for calculation was Ku_{90} based on Rittidech and Pipatpaiboon [8]; they studied in correlation to predict the heat transfer of a CLOHP/CV. Pipatpaiboon tested at 0, 20, 40, 60, 80 and 90 ° from the horizontal axis. The inner diameters for testing were 1.77 and 2.03 mm.

$$Ku_{90} = 0.0004\left[Bo^{2.2}Fr^{1.42}Ja^{1.2}Pr^{1.02}R_{CV}^{1.4}W_e^{0.8}\left(\frac{L_e}{D_i}\right)^{0.5}\left(\frac{\rho_v}{\rho_l}\right)^{0.98}\right]^{0.107} \tag{4}$$

where Ku_{90} is the ratio of heat flux to critical heat flux for the vertical orientation. Bo, Fr, Ja, R_{CV} and We are described and solved by the correlation from Pipatpaiboon and Rittidech [8,19].

The heat transfer rate (Q) of CEOHP and CLOHP/CV was calculated as Eq. (5).

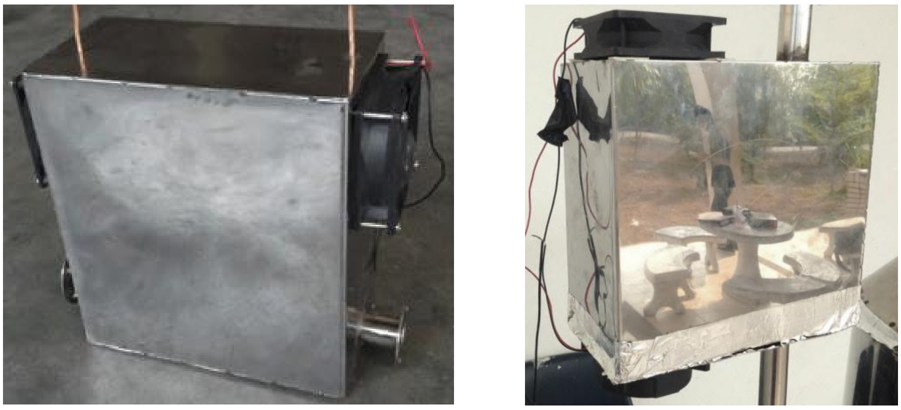
$$Q = A \times q \tag{5}$$

where A is the outside surface area of tube (m^2) and q is heat flux (W/m^2) it can be solved by Eq. (2).

In this research, the lengths of the evaporator and condenser sections were 10 cm. The CEOHP and CLOHP/CV were covered by stainless steel sheets and 2 fans set up at the end of box for air control inlet and outlets of the condenser section as shown in **Figures 2(a)** and **2(b)**. The CEOHP and CLOHP/CV heat exchangers were set up as part of the small size essential oil refiner as shown in **Figure 4**.

The small size essential oil refiner

Figures 3 and **4** show the schematic of experimental setup of a normal small size essential oil refiner and the small size essential oil refiner using OHP for essential oil condensation, respectively. In this experiment, only the condenser section of the small size essential oil refiner was changed. The condenser section of the normal small size essential oil refiner is made from the 2 layers of stainless steel pipe, the inner pipe was the steam pipe of 2.5 cm and the outer pipe (tube for water circulation) was 7.5 cm. The total length of this condenser was 30 cm. For OHP, the inner diameters of the CEOHP and CLOHP/CV were 2 mm. The CEOHP and CLOHP/CV were made from copper capillary tubes. The small size essential oil refiner was made from stainless steel number 304 with the small size essential oil refiner covered by a thermal insulator. The wall thickness of the boiler pot was calculated using Eq. (6) [20]. In this case, the wall thickness of the boiler pot was 2 mm. The steam pipe was made from stainless steel pipe with an inner diameter of 2.5 cm. The electric heater (1,500 W) was set up at the bottom of the pot for heating water.



(a) (b)

Figure 2 The CEOHP and CLOHP/CV heat exchangers with case and fans.

$$t = \frac{p \times d}{2 \times \sigma} \tag{6}$$

where p is the vapor pressure at inner boiler pot (N/mm^2), d is the diameter of boiler pot (mm) and σ is the stress (N/mm^2).

Operating conditions

Two liters of water were added to the pot and then the plant product was placed in the tower distiller. The plant product was 500 g of Eucalyptus leaves as shown in **Figure 5**. In the case of condensation testing using water circulation, the water flow rate was set at 0.12 L/s. While for CEOHP condensation, the air velocity was 5 m/s. The water temperature for testing in the steam pressure pot was set at 100, 110 and 120 °C. The temperatures in this research were measured and recorded every 5 min until 2 h with a Testo 177-t4 v01.10 (best temperature measurement accuracy as ±0.5 °C). The vapor pressure for testing in steam pressure pot was set at 1, 1.5 and 2 bars. The time for testing was 2 h. The essential oil and water were filled into a separatory funnel. When the essential oil and water separated, the water was released. After that the essential oil quantity was measured and recorded. The heat transfer rate (Q) of the CEOHP, CLOHP/CV and water circulation set-ups were calculated using Eq. (7) [21].

$$Q = \dot{m}C_P(T_{out} - T_{in}) \quad (7)$$

where T_{in} and T_{out} are the mean fluid temperature at the inlet and outlet of the OHP condenser section or water circulation, respectively. The term $\dot{m}$ is the mass flow rate of fluid and C_P is the specific heat of the fluid (air or water).

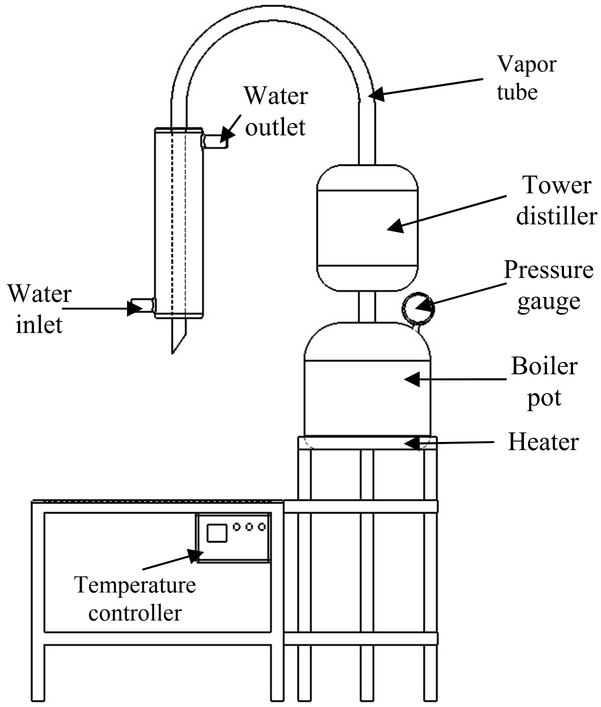


Figure 3 Schematic of the experimental setup of the normal small size essential oil refiner.

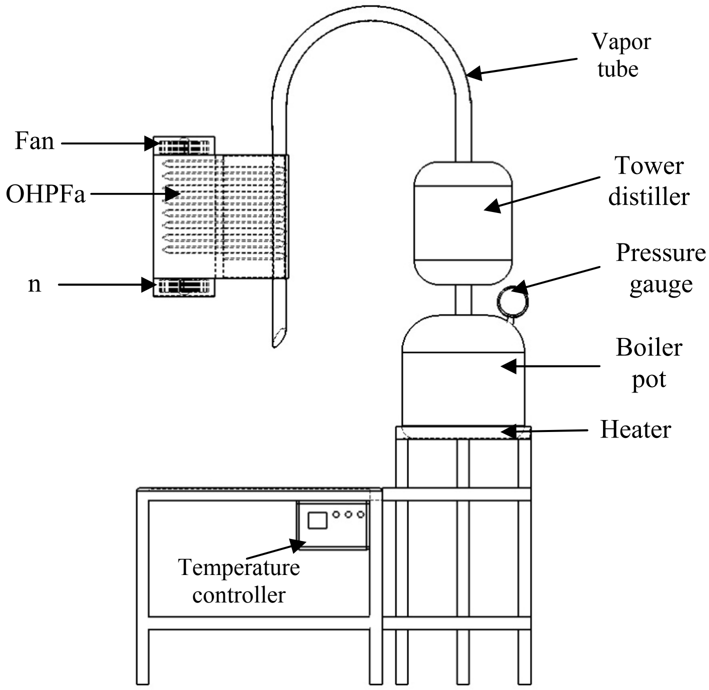


Figure 4 Schematic of the experimental setup of the small size essential oil refiner with OHP condenser.

Figure 5 Eucalyptus leaves used in the experiment.

Results and discussion

The Eucalyptus essential oil quantities obtained using the OHP exchanger for condensation was more than the Eucalyptus essential oil quantities using water circulation for condensation because the OHP can transfer heat from the vapor tube (OHP condenser section box) better than the water condenser as shown in **Figures 6** - **8** where the heat transfer rate of OHP from Eqs. (2) to (5) and (7) are presented. The heat transfer of CLOHP/CV at any pressure and temperature are higher than CEOHP and water circulation because CLOHP/CV has a check valve for controlling the vapor plug from the evaporator section of the OHP to the condenser section of the OHP in one direction. Therefore, the heat transfer rate of the CLOHP/CV was higher than the heat transfer rate of CEOHP providing that the same working fluid is used [18]. If the heat pipe can transfer heat better, it will result in more refined oils. As shown in **Figures 6 - 8**, if the water temperature for testing is higher, the heat transfer of the heat pipe is also higher. The heat transfer of the heat pipe is not influenced by the vapor pressure in the steam pressure pot because the heat transfer of the heat pipe from the equation used and experiments are dependent on the temperature of the evaporator and condenser sections of the heat pipe. Considering the result of the Eucalyptus essential oil quantities, it was found that both the temperature and vapor pressure influenced Eucalyptus essential oil quantities. Increasing the temperature while keeping the vapour pressure constant increased the quantity of Eucalyptus essential oil. Similarly, increasing the vapor pressure at constant temperature gave increased amounts of Eucalyptus essential oil. This suggests that higher water temperature and vapor pressure in the pot allow a greater volume of essential oil to be extracted from the Eucalyptus leaves. The effect of vapor pressures and temperatures on Eucalyptus essential oil quantities are shown in **Figure 9**. The best Eucalyptus essential oil quantity in this paper was 2.96 cc using CLOHP/CV at 2 bars, 120 °C.

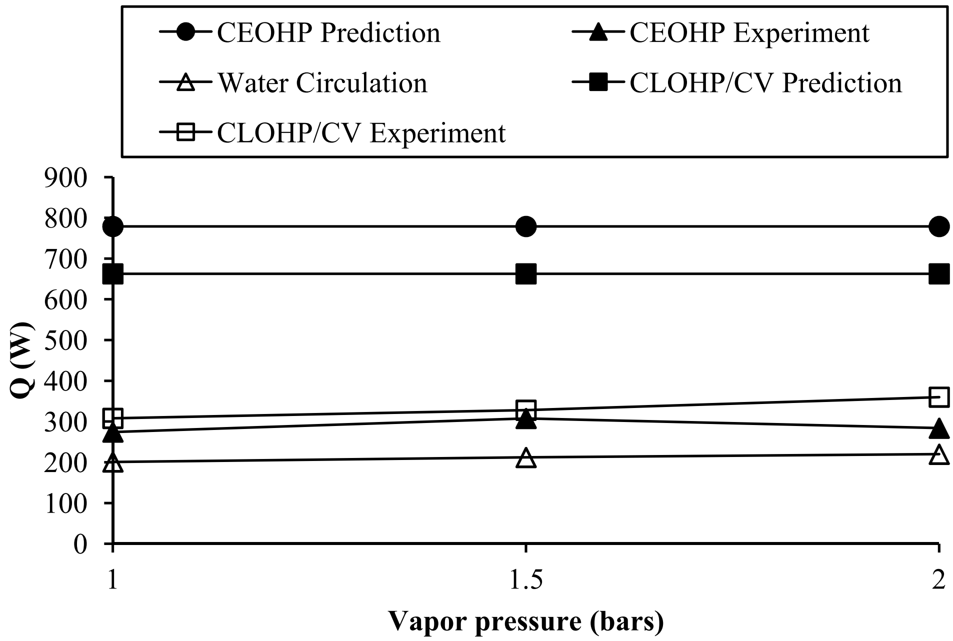


Figure 6 Heat transfer rate of the refiner condenser section at 100 °C.

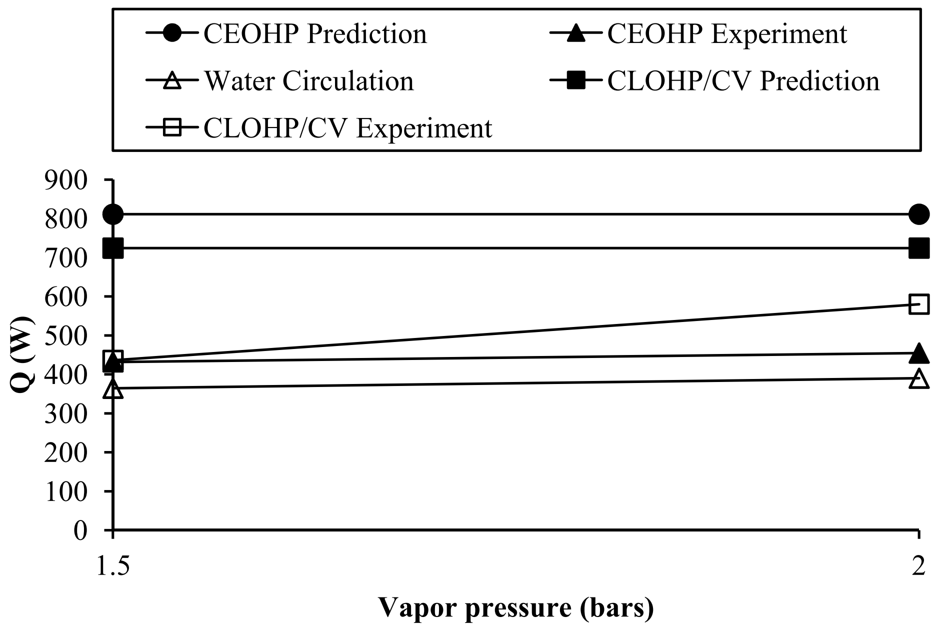


Figure 7 Heat transfer rate of the refiner condenser section at 110 °C.

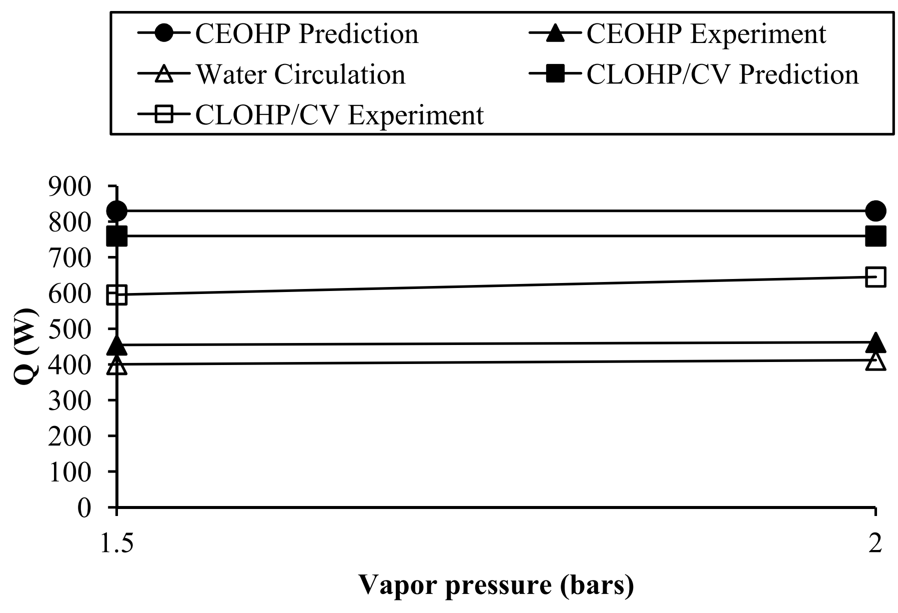


Figure 8 Heat transfer rate of the refiner condenser section at 120 °C.

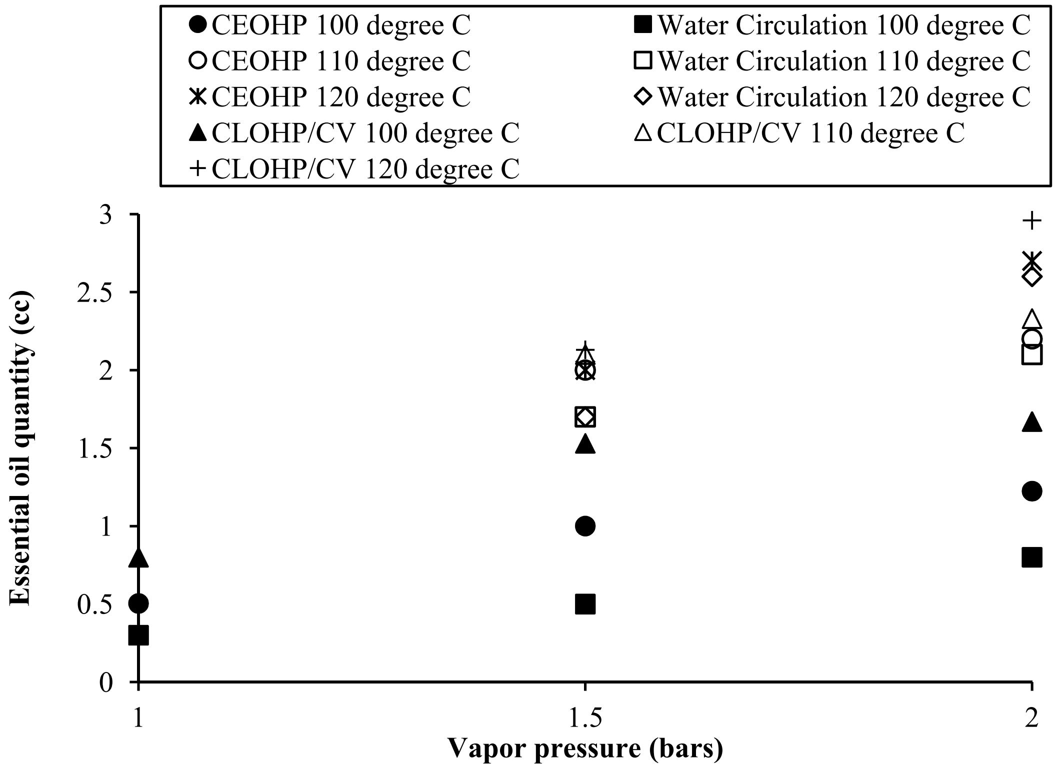


Figure 9 Eucalyptus essential oil quantities at any 1, 1.5 and 2 bars vapor pressure.

Conclusions

The OHP heat exchanger can condense Eucalyptus essential oil. The heat transfers of CLOHP/CV at any pressure and temperature were higher than CEOHP and water circulation. The Eucalyptus essential oil quantity by using OHP for condensation was more than the Eucalyptus essential oil quantity by using water circulation for condensation. The highest Eucalyptus essential oil quantity was 2.96 cc using a CLOHP/CV heat exchanger for condensation. As a result, it is concluded that essential oil condensation can be done using a OHP heat exchanger instead of water circulation.

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