Optimization of small agarwood hydrodistillation systems: An analytical study to determine the required cooling water flow for optimal operation of an agarwood-hydrodistillation system

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Abstract

Cooling systems in a hydrodistillation consists of clevenger type condenser that condensates steam for collecting extracted essential oil. An analytical study was used to compute the required cooling water flow in the condenser to completely change the generated steam from the still to liquid in the heat exchanger. In the simplified model of the counter flow heat exchanger configuration, the Gnielinski correlation was used to calculate the heat transfer coefficient. For variation of the boiler heat flows the corresponding required mass flow rate for optimal operation can be determined from this analytical study. The analyses has shown, that for the given system, a massflow of more than 2000 kg/h is needed to operate at a capacity of 5 kW. Further optimization is needed to operate under reasonable conditions. The results can later be used for optimising the design parameters of the hydrodistillation to extract essential oil at high productivity. Engineering knowledge and fundamentals have to be transferred to the planner and operators to optimize the thermal and hydraulic design of hydro distillation plants, especially in rural areas.

***Keywords**: Heat transfer, Hydrodistillation, Heat exchanger* evaluation, *Gnielinski correlation, agarwood*

Nomenclature

Variables	Description	Unit	Indices	
$\dot{Q}$	Heat flow	W	Hx	Heat exchanger
$\dot{m}$	Mass flow	kg/s	w'	Water inlet
T	Temperature	K	w''	Water outlet
A	Heat transferring surface	m^2	W	Water
w	Fluid velocity	m/s		
ρ	Density	Kg/m^3		
h	Heat transfer coefficient	$W/(m^2\ K)$		
Re	Reynolds number			
Nu	Nusselt number			
Pr	Prandl number			
c	Specific heat capacity	J/(kg K)		
η	Dynamic viscosity			
λ	Heat conductivity	W/(m K)		

Introduction

According to Liu et al. (1) agarwood and its essential oil is used since the 5th century in Chinese medicine and furthermore, more than 18 countries, especially in South East Asia are involved in the trading and processing of agarwood. Essential oils can be extracted from agarwood by hydrodistialation, where the shredded wood is inserted in a water bath and the oil components are solving in the water under heat supply. In the system, the water evaporates at boiling temperature in the still and condensates again in a downflow, watercooled heat exchanger as depicted in figure 1.

Hydrodistillation is a separation of liquid or vapour mixture of two or more substances separated into the fractions of its component of desired purity by the supply and removal of heat. The benefits of hydrodistillation over other distillation processes such as steam distillation and supercritical are found in the low operating temperatures, pressures and simpler operating procedure that reduces the equipment setup and costs, low maintenance and the possibility to be used by small scale farm owners. The lower operating temperatures enables the operator to use available heat source like wood and hydrocarbon gases.

However, at this moment knowledge about the optimal design for the heat and mass transfer of such a hydrodistillation process is scarce which lead to inconsistent quality and productivity of extracted essential oil. In this study, a simplified heat transfer model is set up, to estimate the required cooling water flow, depending on the heat supply. It is estimated, that the operation goal is to produce as much oil as possible in a given time. Here for the energy consumption should be minimal. The governing condition for an optimal operation is supposed to be a complete condensation of the steam to liquid in the heat with no or small sub cooling. The example plant, exanimated in this and future studies is stationed in Kuala Terengganu, where the operator reported an unpredictable oil production and suspected insufficient cooling as reason.

Methology

The schematic diagram of the system is shown in figure 1. In original set up, 4 boilers, fired by industrial ring burner are used to evaporate the water/oil mixture. In a heat exchanger, the evaporated mixture is condensed and the oil concentrate can be extracted from the container beneath. The cooling water flows back to the tank and is then recycled back to the heat exchanger by water pump.

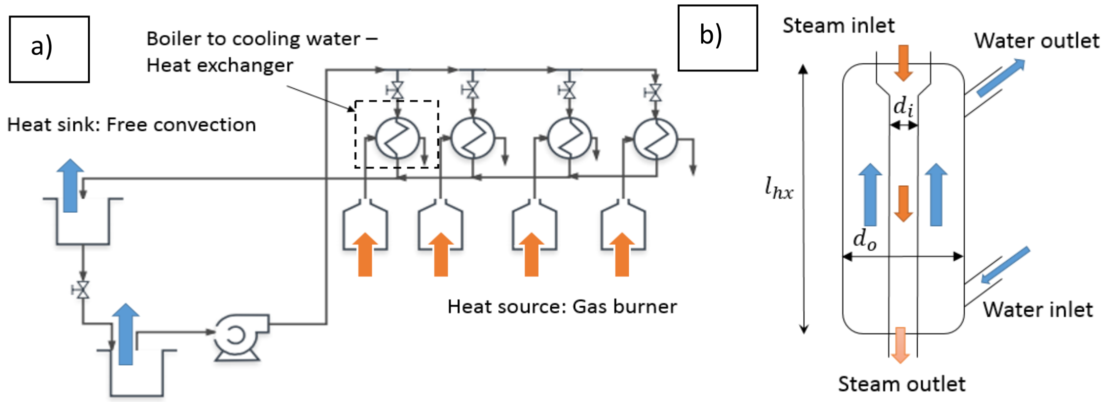

Figure 1 Schematic of a hydrodistillation plan with 4 boilers (a) and the analysed heat exchanger (b)

The first step to optimize a given or design a new cooling system is by determining the required mass flow of cooling water. The operation is estimated to be optimal, when the heat exchanger can just condense all the incoming steam. If the cooling capacity is smaller, a fraction of the outflowing fluid is still in steam part which results a part of the oil cannot be collected. A higher capacity of the heat exchanger is less critical, but will result in higher pumping costs or a bigger, more expensive plumbing system. Therefore, the cooling capacity of the heat exchanger in optimal operation is

$$\dot{Q}_{HX} = \dot{m}_V \cdot \Delta h_V, \quad (1)$$

with the steam mass flow $\dot{m}_V$ and the enthalpy of evaporation Δh_V. The steam massflow can be estimated from the heat balance of the boiler with

$$\dot{Q}_B = \dot{m}_V \cdot \Delta h_V + \dot{Q}_{loss}. \quad (2)$$

If the system is assumed as adiabatic, the heat loss $\dot{Q}_{loss}$ should be zero and the optimal heat exchanger capacity equals the boiler heat flow. The governing equation of the heat exchanger is

$$\dot{Q}_{HX} = A_{HX} \cdot h_{HX} \cdot \Delta T_{lg} \quad (3)$$

with the heat transferring surface A_{HX}, the heat transfer coefficient h_{HX} and the logarithmic mean temperature difference ΔT_{lg}. The surface is given by the geometry of the heat exchanger and the logarithmic mean temperature difference can be calculated by applying the energy balance for the cooling water flow:

$$\dot{Q}_{HX} = \dot{m}_w \cdot c_w \cdot (T_{w''} - T_{w'}). \quad (4)$$

For the heat transfer coefficient, it is assumed, that the heat transfer coefficient by condensation and the heat conduction in the wall is magnitudes higher than the heat

transfer coefficient by forced convection in the water flow, though only the heat transfer coefficient of the water has to be estimated. Here for the dimensionless Reynolds number $Re = w_w \cdot rho_w \cdot d_H/\eta_W$, the Nusselt number $Nu = h_{hx} \cdot d_H/\lambda_w$ and the Prandtl number $Pr = \eta \cdot c/\lambda$ are defined.
To estimate the Nusselt number and consequently the heat transfer coefficient, the Gnielinski equation (2) is used:

$$Nu = \frac{\left(\frac{f}{8}\right) \cdot (Re_w - 1000) \cdot \mathrm{Pr}}{1.07 + 12.7 \cdot \frac{\sqrt{f}}{8} \cdot (Pr^{\frac{2}{3}} - 1\ )} \tag{5}$$

with the friction factor

$$f = (1.82 \cdot \lg(Re) - 1.64)^{-2} \tag{6}$$

and with the conservation of mass

$$\dot{m}_w = w_w \cdot A_w \cdot \rho_w \tag{7}$$

Taler et al. (3) found good agreement while comparing the results of the Gnielinski equation with experimental data from different sources ((4) (5) (6) (7)), for high Reynolds numbers. The set of equations (1) to (7) delivers the cooling water mass flow rate, the outlet temperature of the cooling water and the mass flow rate of the condensate for given heat exchanger geometry, fluid properties and boiler heat flow. To solve the equations the software Engineering Equation Solver (EES) is used.

A given hydrodistillation plant shall be analysed and optimization suggestion shall be made regarding the cooling system. To estimate the required cooling water massflow, one heat exchanger is analysed. The heat exchanger geometry is given in figure 1 with the inner diameter $d_i = 1.3$ cm, the outer diameter $d_i = 4.5$ cm and the length $l_{hx} = 54$ cm. The heat flow supplied to the boiler is varied between 500 and 7000 W. The inlet temperature of the cooling water is used as a variable parameter.

Results

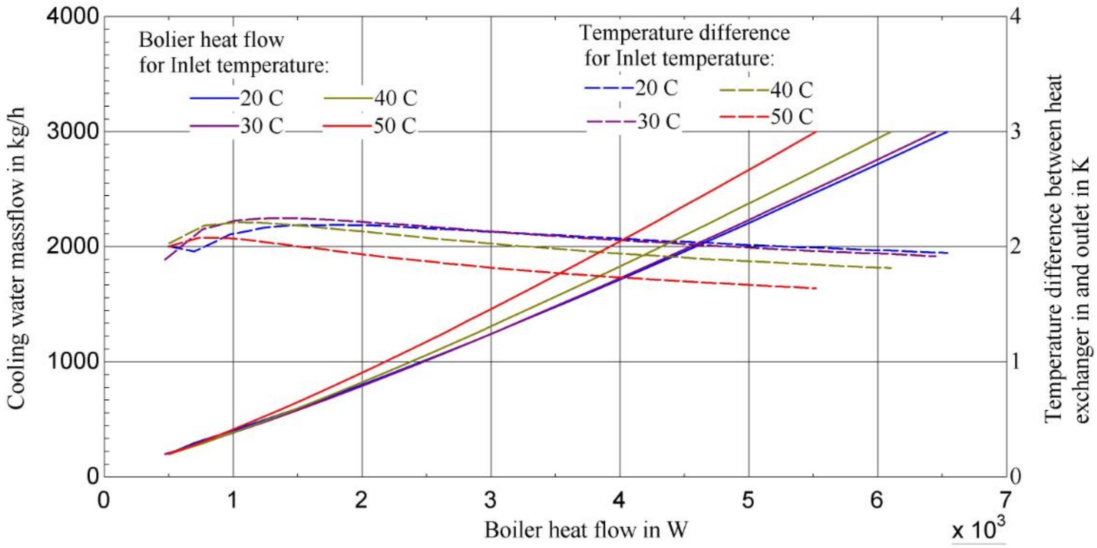

Figure 2 Required cooling water mass flow for optimal operation and correspondending condensate flow for one boiler

In figure 2, the characteristic of the boiler is shown. It can be seen that the required cooling water flow for optimal operation is rising almost linear with boiler heat flow. A higher inlet temperature of the water increases the required massflow. A inlet temperature lower than 20°C on the other hand doesn't significantly decrease the required massflow compared to 30°C. The temperature difference between inlet and outlet observed to be in a range of 1.7 to 2.2K for the entire operation range, whereby higher inlet temperatures result in a smaller temperature difference. The small temperature difference can be seen as a first indicator for optimization potential of the heat exchanger. Due to either a small effective surface or a low heat transfer coefficient due to slow fluid flow, the heat exchanger efficiency was found to be in a range of only 2 to 4 %. The flow of cooling water can be assumed turbulent, with Reynolds numbers in a range from 5000 to 50000. A dimensionless presentation of data is not presented here, to keep the results easier to interpret for planner and operator.

Summary and Outlook

This technical report presents the first step of a thermal and hydraulic optimization of hydrodistillation plants. The results will be used to optimize or design the piping and pumping system as well as the heat sink and the heat source and test and compare the results to a reference system experimentally. The optimization of the heat exchanger itself will also be evaluated in the future research, since a low heat exchanger efficiency of 2 to 4 percent was found. Here for, a parametric study, varying the heat exchanger geometry will be conducted as next step.

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