

A REVIEW OF IMPROVEMENTS TO THE LIQUID COLLECTION SYSTEM USED IN THE PYROLYSIS PROCESS FOR PRODUCING LIQUID SMOKE

Nasruddin A. Abdullah¹, Nandy Putra^{1*}, Imansyah Ibnu Hakim¹, Raldi A.Koestoer¹

¹*Heat Transfer Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*

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ABSTRACT

Liquid smoke can be produced by using the pyrolysis process. Biomass, as the raw material, is heated in a pyrolysis reactor to generate pyrolysis vapor. The pyrolysis vapors coming from the reactor are condensed in a liquid collection system to produce liquid smoke. A liquid collection system is a device used to convert smoke into liquid. Liquid smoke is often also called bio-oil, which is widely used as a fuel, as a preservative, and as other chemical substances. The objective of this paper was to provide the latest information on improving the liquid collection system from existing papers, and conclude with some inputs and application strategies. Studies were performed using the product parameters, equipment, and operational conditions referred to in the existing journal articles. Using a proper liquid collection system will give a better result in the liquid collection process.

Keywords: Biomass; Bio-oil; Liquid collection system; Liquid smoke; Pyrolysis

1. INTRODUCTION

Turning biomass into a useful product is a positive thing that can increase productivity and the economic level of society. The biomass used to produce liquid smoke comes from waste or from many production processes. This biomass, as a raw material, consists of cellulose, hemicellulose, lignin, and smaller amounts of other organic compounds (Bridgwater, 1999). There is an abundance of biomass resources throughout the world; in general, most biomass is obtained from palm oil, palm, corn, rice, and sugarcane, though slightly smaller amounts are obtained from other sources.

Liquid smoke is a liquid produced from the decomposition process of biomass. It can be acquired by extracting it from biomass using the pyrolysis process, which is also known as pyrolysis liquid (Bridgwater, 2012; Sharma et al., 2015). In the fast pyrolysis process, a thermal decomposition of biomass occurs without the involvement of oxygen inside the process (Bridgwater, 2012); this process occurs at a middle range temperature and with high rate flows on biomass particles, and the vapor leaves the reaction zone shortly after it is produced (Czernik & Bridgwater, 2004). In the fast pyrolysis process, biomass is decomposed to rapidly produce pyrolysis vapor, aerosol, carbon, and non-condensable gas. Through the condensation process, using a liquid collection system (LCS), a dark brown liquid is produced; the heating value of this liquid is almost a half that of conventional oil (Bridgwater & Peacocke, 2000).

Liquid smoke is known by many other terms: wood vinegar, bio-oil, pyrolysis liquid, pyrolysis oil, bio-crude oil, biofuel oil, pyrolytic tar, pyrolytic acid, wood liquid, and wood oil. At

*Corresponding author's email: nandyputra@eng.ui.ac.id, Tel: + 62-21-7270032, Fax: +62-21-7270033
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the present, liquid smoke is already widely used in the food industry. Liquid smoke can be used as a flavoring, has a specific scent, is antimicrobial, and is an antioxidant thus suitable for preservative. Liquid smoke has been used commercially as an antibacterial (Suñenet al., 2001; Milly et al., 2005). Liquid smoke has the ability to preserve food as a result of its antimicrobial compounds and antioxidants, such as aldehydes, carboxylic acids, and phenols (Leroi & Joffraud, 2000; Rørvik, 2000).

One of the most important components in producing liquid smoke is the LCS. In this component, the vapor generated by the reactor is cooled and liquefied; whether the cooling is rapid or slow depends on the type of LCS. Condensing the vapor in an LCS is a difficult part of the operational process of fast pyrolysis because the pyrolysis vapor contains more aerosol than the condensable vapor (Bridgwater & Peacocke, 2000). The cooling system process could be improved by using a vapor chamber (Hasnanet al., 2017).

Figure 1 shows the production schematic of liquid smoke. Starting with the raw-material preparation, next comes a reactor for generating pyrolysis vapor, then a cyclone to separate the solid particles from the vapor, and finally the pyrolysis vapor is liquefied, for which the a part of the equipment is the LCS. The products of this process are liquid smoke, non-condensable gas, and charcoal.

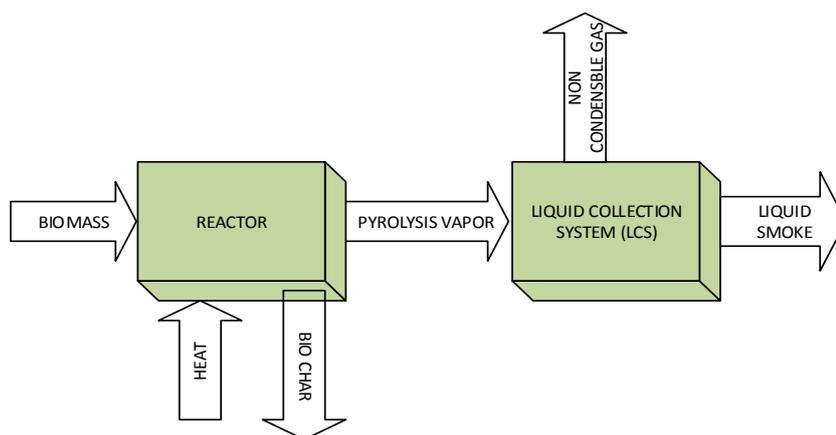


Figure 1 Production schematic of liquid smoke

Although, in fact, many researchers have focused on the pyrolysis reactor (Blasi, 2000; Babu & Chaurasia, 2004), the cyclone separator, or even electrostatic precipitators (ESPs) used in pyrolysis technology (Luo et al., 2015), the LCS is the main component in producing liquid smoke. Therefore, this paper will summarize the potential improvements in the LCS for producing liquid smoke. It is necessary to provide an overview of the improvements and research opportunities that can be performed, and this paper will provide information about the suggested development of LCSs, both from experiments and simulations. The LCS requires rapid cooling to minimize the second reaction and for it to be able to condense the pyrolysis vapor. The product that is condensed in the LCS has a very low partial pressure; this condition is crucial to the LCS process design (Bridgwater, 2012). The objective of this paper is to provide the latest information on improvements in the LCS, and conclude with some inputs and application strategies.

Several types of heat exchanger are commonly applied in LCS, including a tubular heat exchanger, cyclone condenser, spray column, double surface condenser, scrubber, and several other types. The components that enter the LCS can be classified into three categories based on their physical condition. These are non-condensable gases, vapor, aerosols, and a little charcoal that is not trapped in the cyclone. The non-condensable gases consist of hydrogen,

carbon monoxide, carbon dioxide, and other light hydrocarbons produced by the reaction of the pyrolysis process; the amount of non-condensable gases ranges from 10–20 wt% of pyrolysis products (Mohan et al., 2006).

The condenser design for the fraction of each compound in the pyrolysis process is based on the operational temperature of the heat exchanger. The boiling point, density, vapor pressure, and molecular weight of some liquid smoke compounds will affect the condensation processes in the LCS. The vapor produced in the reactor contains many compounds from the cooling process, such as water and organic substances; these substances can be condensed. There are also some other organic compounds produced, consisting of carboxylic acids, alcohol, esters, and phenols, all of which have the different boiling point. The vapor that is generated by the reactor is cooled and liquefied in the LCS, which provides rapid cooling or slow cooling depending on the type of LCS. How best to condense the relative amount of vapor and aerosol is very difficult to ascertain, due to each substance being partially transformed into other forms, depending on the environmental conditions of the temperature and constituents. Some reports state that 90% vapor flows out of the pyrolysis reactor in the aerosol form it is highly dependent on raw materials and the reaction conditions (Daugaard, 2003).

The Liquid in LCS will be collected base on different properties of pyrolysis vapor fractionally, based on the saturation temperature of each substance. Each fraction of the compound in the vapor stream will condense when the temperature of vapor drops below the fraction's boiling point or saturation temperature. Saturation temperature T_{sat} can be calculated from the vapor pressure P_v of each compound from the vapor stream using the Clausius-Clapeyron equation:

$$\ln \left(\frac{P_v}{P_o} \right) = \frac{\Delta H_{vap}}{R} \left(\frac{1}{T_o} - \frac{1}{T_{sat}} \right) \quad (1)$$

The following equation is used to obtain vapor pressure:

$$P_v = \frac{m_f C_{oil} R_u T_o}{MW} \quad (2)$$

where P_o is the saturation pressure at standard temperature; T_o and $(\Delta H)_{vap}$ are the vapor temperature and enthalpy from the compound, respectively; R_u is universal gas constant; T_o is the standard temperature at volumetric flows; and MW is the molecular weight.

2. METHODOLOGY

The LCS is a challenge for the researcher when it comes to producing liquid smoke; the literature discusses several different options on the kind of LCS that may be used. In general, LCSs can be classified into three main categories, which are spray tower or column, heat exchanger, and a combination of both. Furthermore, ESPs are also used to capture the aerosols outside of the condensation system, whether using a spray column, heat exchanger, or the combination of both. The raw materials are influential in determining the type of LCS that is needed. Some reports explain that 90% of the vapor that flows out from the pyrolysis reactor is in aerosol form. This is highly dependent on the raw material and the reaction condition in the pyrolysis reactor. Studies have been performed using the product parameters, equipment, and operational conditions referred to in the existing paper. Using an appropriate LCS will result in a liquefaction process that is more effective and efficient.

3. LIQUID COLLECTION SYSTEM (LCS)

3.1. LCS with Spray Quench and Distillation Column

Large-scale systems usually use a spray-quench column for condensation. The liquid smoke produced is cooled prior to entering the chiller, then it is circulated in the quenching column by using a pump, and is sprayed to a hot vapor in the column. This process will transfer heat from the hot fluid to the cold fluid directly, and will condense the vapors when the saturation temperatures are reached. The weakness of this system is that it is very difficult to fractionate the product because it is very difficult to control the temperature of the cooling.

Some studies have been conducted relating to LCSs, including the spray tower or column type. For example, a two-level, jacketed, countercurrent spray column, which has a diameter of 0.07 m and a height of 1.68 m. An Ordina shell 941 was used to spray the liquid oil at start-up to control the condensing temperature at 1°C, in (Westerhof et al., 2007) study. The first-stage condenser is known as the prime condenser, which operates at a temperature 20°C, and the second condenser maintains a temperature of 0°C, and is intended to condense any residual vapor that was not condensed in the first condenser. By applying this method it is possible to control the moisture content of the product in a way other than controlling the water content in the raw materials, which will be decomposed in the reactor.

Lindfors et al. (2014) used a sieve-plate column (scrubber) on the pyrolysis vapor to condense it in the first stage of liquid recovery. To condense the vapor generated by the reactor in the first stage, direct and indirect cooling were applied to the liquid from the hot vapor; inlet direct cooling was applied in the sieve-plate column, then the thermal degradation reaction of the collected pyrolysis liquids was reduced (Lindfors et al., 2014). A hydrocarbon liquid was used as the liquid cooler in the scrubber. To adjust the outlet gas temperature, indirect cooling was applied by varying the cooling temperatures.

Fractional distillation is another type of LCS. The 47.5 mm ID fractional distillation column comprises four stages and has a total length of 430 mm. Each stage was packed with 140.0 g of 5 mm glass ballotini in (Yinet al., 2013) study. The pyrolysis vapors were condensed in the different stages in the fractional distillation column. Furthermore, the four stages of heat exchange and one stage of ESP were installed to separate the liquid smoke. Each stage of the condenser was maintained at average temperatures of 310K, 298K, 296.5K, and 297K, respectively. Resident time of each condenser was around 2.4 seconds. The remaining vapor was captured by using ESP.

To reduce the water content in the bio-oil, two stages of cyclone condenser were installed complete with a stage of ESP in (Gootyet al., 2014) study. The first condenser was maintained at a temperature of 80°C in order to condense the heavy fraction of the liquid smoke. The vapor coming out from the first-stage condenser flowed into the ESP to absorb its aerosol. In the second condenser, the temperature was maintained at 10°C to condense all of the moisture content and the light fraction of vapor; the same method was also employed to minimize the water content in the product up to 1 wt%, and get better efficiency.

3.2. LCS with Heat-exchanger-type Cooling

Heat exchangers in LCSs can cause slow cooling and can condense the components produced from lignin, but this process tends to cause a blockage in the heat exchanger due to the high viscosity of the liquid components produced from lignin (Bridgwater et al., 1999). It is easier to use a heat exchanger to control the temperature, so this is easier to implement in the condensation process that aims to fractionate the products based on the boiling point of each liquid-smoke product.

Some previous research has been done on LCSs that use heat exchangers in the cooling process. In (Lédécet al., 2007) research, a heat exchanger was installed in series. They used water as a

cooling fluid, and the diameter of the heat exchanger was 0.01 m and its length was 0.5 m. The heavy fraction of the liquid smoke was condensed by using air, and a refrigerated coil with temperature 258 K was mounted at the end of the system was to condense the light fractions of the liquid smoke.

The heat exchanger used can be followed by two stages of ESP and two stages of another heat exchanger to condense the pyrolysis vapor (Predel & Kaminsky, 1998). A three-stage of heat exchanger can also be used, which is equipped with two stages of ESP and a glass-wool filter to capture the residual aerosols. The temperature of the heat exchanger is adjusted to the boiling point for each fractionation (Pollard et al., 2012). The total decrease in temperature that occurs in all four tubes is 278°C and cooling rate is 60°C/sec (Boateng et al., 2007).

In (Miao et al., 2004) study, hot water was circulated in the first-stage condenser to reduce the vapor temperature and condense the pyrolysis vapor at the boiling point, while the second stage used ice to condense the remaining pyrolysis vapor. A single stage of the condenser was used by (Yuliansyah et al., 2015) to liquefy the vapor with low-density polyethylene (LDPE) used as the raw material.

Three condensers (of 10 cm diameter × 200 cm length) were used in series along with a coolant-temperature controller with a water jacket in Kim et al.'s (2016) study. Hot water at 85–90°C was circulated at the first condenser. Water was used as the coolant liquid in the second condenser with the temperature maintained at 45–50°C, the temperature was maintained at 10–15°C in the third condenser. The outgoing vapor temperatures in each condenser are 121°C, 107°C, and 25°C for the first, second, and third condensers, respectively. A multi-stage condenser needs a sweeping gas to flow the vapor through the condenser; in the multi-stage condenser, the bio-oil fractionation temperature, bio-oil composition, water content, viscosity, and density are influenced by the flow rate of the sweeping gas. The temperature increase will influence the composition and water content of the bio-oil in the third condenser. Two glass-trap condensers in the LCS were filled cooling fluid in (Yang & Ani, 2016) research to liquefy the vapor generated by a microwave reactor.

Two stages and three stages of condensing have been applied to dilute the condensable pyrolysis vapor in (Schulzke et al., 2016) study. The experiment with two-stage condenser was conducted, and used a vapor temperature of 539°C. The temperature was kept at 90°C in the first-stage cooler and ESP. The vapor temperature leaving the first stage was 89°C. In the second stage, the cooling temperature was maintained at 2°C with water used as the cooling fluid. The three-stage condenser was installed with a different cooling temperature for each condenser; these temperatures were 120°C, 90°C, and 2°C, and the temperature of the vapor that entered the first condenser was 550°C. The temperature of the vapors leaving the first and second condensers were 115°C and 87°C, respectively. The higher boiling fraction shows a high heat value, and was low in water and acid. Water and some kind of acid will be obtained from low-temperature cooling.

An impinge type of condenser train system was used to collect liquid from pyrolysis vapor in (Kuo et al., 2017) study. This consisted of four condenser tubes, each with a size of 10×20 cm, installed in series. The tube was cooled using ice, and, at the end, the pyrolysis vapors were condensed at two different temperatures outside distillation column after leaving the fractional distillation column. At the bottom of the distillation column, bio-oil was collected at 136°C, and is regarded as a heavier oil. Meanwhile, bio-oils were collected at 20°C and 0°C as lighter oils. And the remaining of non-condensable gases were vent to the atmosphere.

(Mazlan et al., 2015) used a cooled ethylene-glycol bath to provide the cooling fluid, which was immersed into two condensers to liquefy the vapor at below -10°C to improve condensation efficiency. (Jinet et al., 2015) used a series of four ice-bath condensers immersed in ice water to

condense the pyrolysis vapor.

An LCS consisting of three condensers connected in series (condenser 1, C-ESP, and condenser 3) was used in (Liet al., 2015) research. The water was condensed primarily in condenser 3, a higher temperature was maintained to collect the heavy components in condenser 1 at 80°C, and the temperature in C-ESP was controlled at 70°C. To recover the water and light components from the vapor, condenser 3 was immersed in an ice-water bath.

An ice-water-cooled impinge type of LCS was combined with a countercurrent, double-pipe condenser in (Luo et al., 2017) experiment, in which the vapors from the reactor entered the ice-water-cooled impinge and went into the condenser at the bottom. The cooling fluid used was propylene glycol/water, of 50/50 vol %, with an inlet temperature of -10°C. At this stage, the light fraction of the bio-oil was collected.

In (Messina et al., 2017) study, volatile products were condensed and collected using a series of three condensers at -10°C, which was immersed in the thermostatic bath.

3.3. Combination of LCS Spray Column and Heat Exchanger

To determine the advantages of each type of LCS, a merger of these two processes was applied. A spray column is able to condense vapors in larger quantities, while it is easier to control the temperature in a heat exchanger, so it is easier to complete fractional condensation of the vapor. (Westerhof et al., 2007) employed two condensers that were built with several nozzles and coupled to a heat exchanger inside. A pump was used to circulate a coolant into the condenser for direct cooling of the pyrolysis vapor through the condenser. Figure 2 shows the combined LCS process comprising a heat exchanger and two quench columns. The pyrolysis vapors entered the column and were sprayed with a coolant before being cooled in a heat exchanger. The same process occurred in the next column. The type of condenser was a cyclonic condenser.

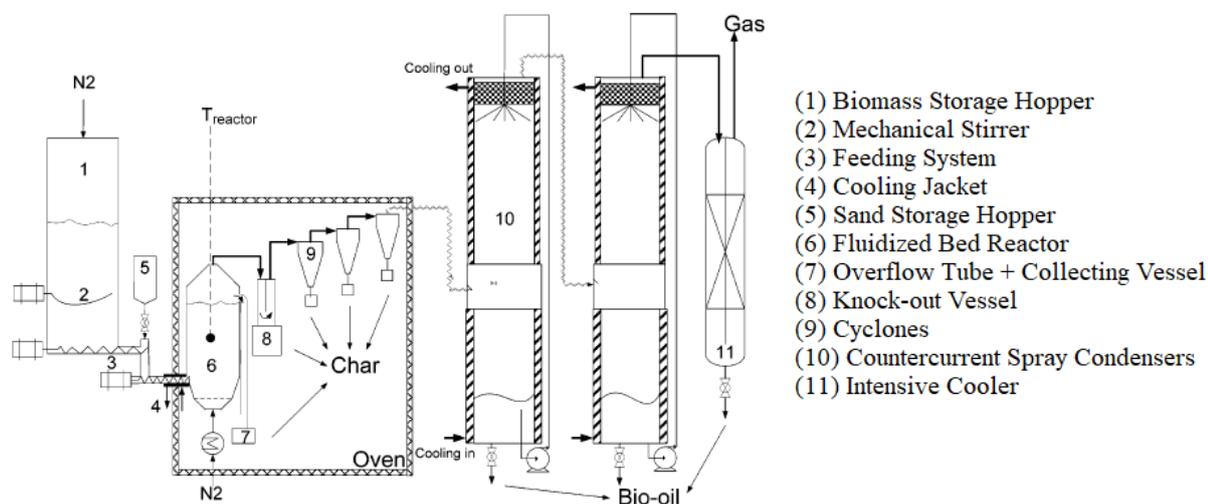


Figure 2 Combined LCS process with two quench columns (Westerhof et al., 2007)

The use of multiple sprayers combined with heat exchangers can accelerate the liquefaction process and rapidly change the pyrolysis vapor. The amount of heat is more easily absorbed in an LCS when these two processes are combined (Zhenget al., 2008). A pipe-bundle quencher was used by (Luo et al., 2004) to condense the pyrolysis vapor produced by the reactor, and water was used as cooling fluid. To obtain the fractions of bio-oil in accordance with the conditions of the boiling points of each component, (Schulzke et al., 2016) used a four-stage condenser. Each condenser was maintained at a certain temperature, these temperatures being 300°C, 100°C, 0°C, and -20°C, respectively. Nearly 90% of the lighter components were condensed in the condenser,

which was maintained at 0°C.

Two quencher columns equipped with condensers connected in series were installed to quench condensable and non-condensable gas in (Wuet al., 2016) study. A spraying column and a heat-exchanger cooler (shell-tubetype) were employed for each condenser and a chilling machine with a coolant temperature of 288K was equipped for each shell and tube cooler to control the process temperature in the condenser. In the first condenser, the bio-oil temperature was 313–323K and it was 293K in the second condenser. ESP was used to capture the aerosols from the condenser; the yield of the product depended on the raw materials that were used. In the series of condensers, bio-oils were collected of almost 88 wt%, 9.8 wt%, 1.9wt%, respectively for the Douglas-fir sawdust.

Table 1The summary of LCS type and classification

LCS Classification	Researcher	Year	Type of LCS
LCS with spray-quench column and distillation column	Westerhof et al.	2007	Two-level, jacketed, countercurrent spray column
	Lindfors	2014	Sieve-plate column (Scrubber)
	Yin et al.	2013	Fractional distillation column
	Gooty et al.	2014	Two stages of cyclone condenser and a stage of ESP
LCS with heat-exchanger-type cooling	Predel and Kaminsky	1998	Two stages of heat exchanger followed by two stages of ESP
	Miao et al.	2004	One stage of condenser with hot water and two stages of condenser with ice water
	Yuliansyah et al.	2015	Vertical and one stage condenser
	Lédé et al.	2007	Series of two heat exchangers
	Pollard et al.	2012	Three stages of heat exchanger followed by two stages of ESP
	Mazlan et al.	2015	Two condensers immersed into a cooled ethylene-glycol bath
	Jin et al.	2015	Four condensers immersed into an ice bath
	Li et al.	2015	Two condensers in series and one ESP
	Kim et al.	2016	Three condensers in series
	Schulzke et al.	2016	Two stages and followed by three stages of condensers
	Yang and Ani	2016	Glass-trap condenser
	Kuo et al.	2017	Four stages of an impinge type of condenser train
	Luo et al.	2017	One countercurrent, double-pipe impinge-type LCS cooled in ice water
Messina et al.	2017	Three condensers immersed into a thermostatic bath	
Combination of an LCS spray column and heat exchanger	Luo et al.	2004	One pipe-bundle quencher
	Westerhof et al.	2007	Two quenching columns combined with a cyclonic condenser
	Schulzke et al.	2016	Four stages of condenser
	Wu et al.	2016	Two quencher spraying columns equipped with condensers in series and an ESP
	Huang et al.	2016	One distillation column and two water condensers

Huang et al. (2016) used an LCS equipped with a distillation column and two water condensers.

The bio-oils were condensed at 120°C and 80°C in the column, and at 0°C for water condenser; the bio-oils collected in the column are heavy fractions and those collected in the water condenser are the light fractions.

A summary of types of LCS improvements are shown in Table 1.

4. CONCLUSION

The improvement of LCSs has become a serious concern of researchers with respect to the vapor condensation process. A spray tower or column has been used in LCSs to condense large quantities of liquid smoke without fractionation processes. Heat exchangers are widely applied in the condensation processes for liquid smoke due to the ease of controlling the cooling temperature. A heat exchanger is more suitable for using as the LCS to separate the heavy fractions and light fractions in liquid smoke. Using a higher boiling fraction showed a high heating value, and a result low in water and acid, which are obtained at a low temperature of cooling fluid. From the assessment of LCSs it can be concluded that there are improvements that can be made, such as the use of heat exchangers to produce liquid smoke for each fraction according to their boiling point. The current trends in LCS research for pyrolysis suggest fractional condensation can be used to obtain the required products. A suitable design is needed for the heat exchanger as a result of the thermal properties of the vapor. Research on liquid smoke based on thermofluids still needs to be conducted. There is a lack of data on thermal properties, especially for local materials from Indonesia, which provides opportunities for researchers from Indonesia to study LCSs more, especially those based on thermofluids.

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