International Journal of Technology (2018) 6: 1236-1245
ISSN 2086-9614 

# AN EXPERIMENTAL STUDY OF THE VAPOR TEMPERATURE IN THE REACTION ZONE FOR PRODUCING LIQUID FROM CAMPHOR WOOD IN A NON-SWEEPING GAS FIXED-BED PYROLYSIS REACTOR

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(Received: May 2018 / Revised: July 2018 / Accepted: October 2018)

## ABSTRACT

The liquids produced by the pyrolysis process with biomass as the raw material are popularly called bio-oil. The reaction zone temperature in the pyrolysis process affects the liquid yield in a non-sweeping gas fixed-bed reactor. This research aims to obtain the effect of temperature in the reaction zone on the liquid yield. Camphor wood was fed into the reactor as raw material. An electric heater was controlled using the proportional integral differential (PID) controller to keep the reactor temperature constant at 500°C as an optimum decomposition temperature. To control the vapor temperature in the reaction zone, an electric heater was mounted on the wall of the reaction zone, which was equipped with a PID controller to keep the temperature constant. To convert the pyrolysis vapor into liquid, a double pipe condenser was used in the system. This study showed that the liquid yield increases as the vapor temperature increases. The rise in vapor temperature from an ambient temperature to 200°C increases the liquid yield 17.0 wt% with a low heating rate, 5 wt% with a heating rate of 8°C/minute and 4.5 wt% with a heating rate of 17°C/minute. Early condensation occurred due to the low temperature of the vapor at the reaction zone.

*Keywords:* Camphor wood; Fixed-bed pyrolysis reactor; Liquid yield; Reaction zone; Vapor temperature

## 1. INTRODUCTION

Processing wood waste and plant material into a useful product can reduce environmental problems. Camphor wood (*Dryobalanops lanceolate*) is widely available in Indonesia and can be used as an industrial material. Wood waste increases along with the increase in production. This wood waste can be converted into a liquid product. The pyrolysis process is commonly used to convert biomass into bio-oil (Demirbaş, 2001). The reactor is an important tool needed to produce bio-oil and the type of reactor affects the yield of liquid produced (Guedes et al., 2018). Fixed-bed reactors have been widely used in research on the pyrolysis process (Liu et al., 2012; Mohamed et al., 2014; Bordoloi et al., 2016; Garg et al., 2016; Wang et al., 2016; Abdullah et al., 2018). Some operational variables affect the liquid yield and the composition of bio-oil, such as the reaction temperature (Tsai et al., 2007; Uçar & Karagöz, 2009; Butler et al., 2011), the vapor resident times (Scott et al., 1999; Azizi et al., 2018), the size of the feed particles (Demiral & Şensöz, 2006; Aylón et al., 2008; Lédé & Authier, 2015), the biomass heating rates

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Permalink/DOI: https://doi.org/10.14716/ijtech.v9i6.2356

(Salehi et al., 2009; Sukiran et al., 2009; Kabir et al., 2017), the effect of sweeping gas (Uzun et al., 2006; Zeng et al., 2017), the effect of the biomass type, the influence of mineral matter/metal ions, and the effect of the initial moisture content of the biomass (Akhtar & Amin, 2012).

The low pressure and low temperature result in early condensation of the hot vapor on the inside walls of the reaction zone. The use of sweeping gas in the pyrolysis process for purging pyrolysis vapor shortens the residence time in the reaction zone. Rapid cooling of the vapor is needed to increase liquid yield (Encinar et al., 2000). Demiral et al. (2012) reported the increasing liquid yield due to the increasing of the pyrolysis temperature from 400 to 500°C. The vapor produced by the reactor flows into the reaction zone; in this reaction zone, the vapor must go through a liquid collection system (LCS) to change the phase from a vapor into a liquid. The vapor pressure is affected by the partial pressure of each compound. To purge the vapor from the reaction into the LCS, sweeping gas is injected into the system. The use of sweeping gas purges the hot vapor rapidly and maximizes the liquid yield. The effect of the sweeping gas influences the residence time of vapor in the reaction zone because it transports the vapor to the LCS immediately. The vapor chamber was used to increase the cooling process (Hasnan et al., 2017). The pressure in the reaction zone is quite low due to its low temperature. Water vapor, $N_2$, and Ar are commonly used as the sweeping gas. Nitrogen is frequently chosen due to its cheapness (Uzun et al., 2006). The use of nitrogen as a sweeping gas would incur additional operating costs and an additional process.

Many papers have discussed and analyzed the influence of the decomposition temperature, the type of reactor, the particle size, pyrolysis type, sweeping gas, heating rate, but few discuss the vapor resident time (Guedes et al., 2018). This paper will investigate the influence of the reaction zone temperature on the yield of liquid bio-oil produced. Camphor waste woods are used as the feedstock.

## 2. MATERIALS AND METHODS

### 2.1. Sample Preparation

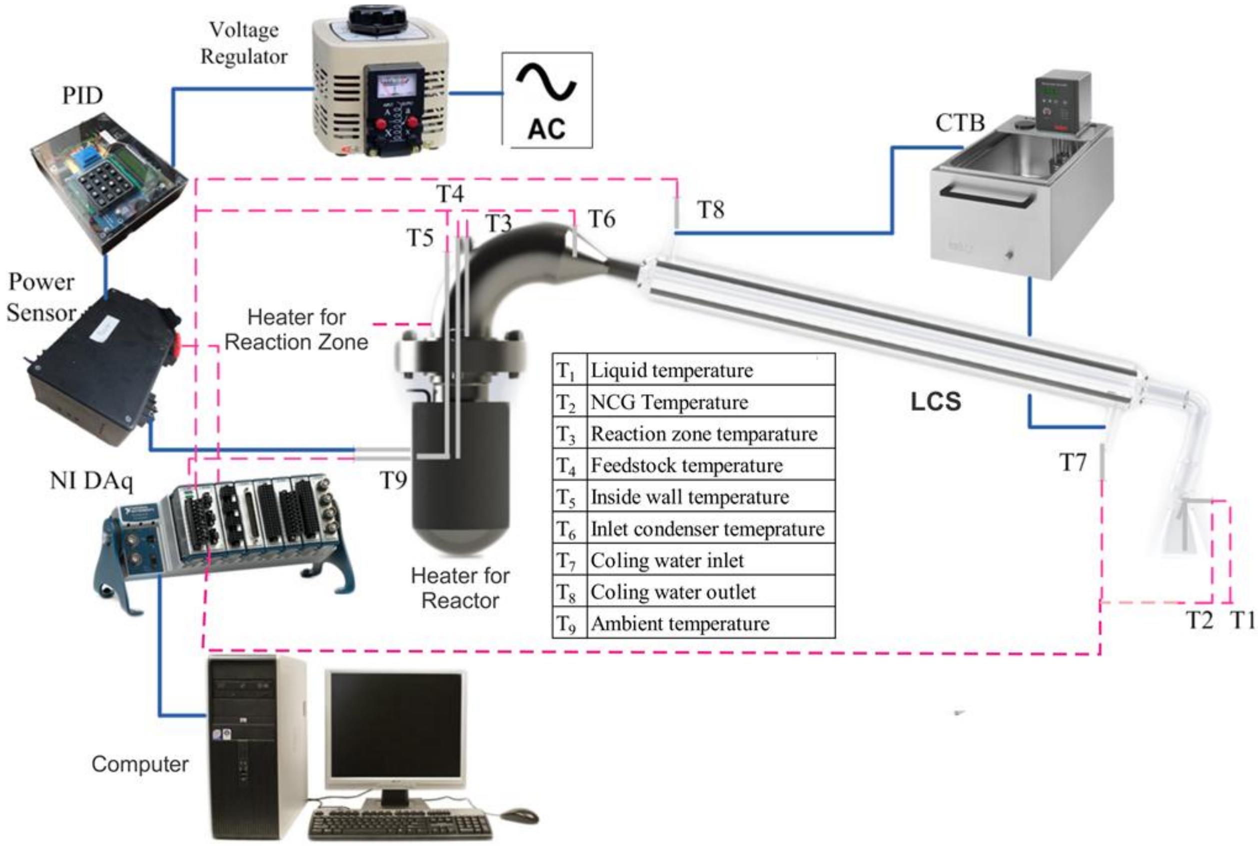
The material used as feedstock in the reactor is waste wood from the local furniture industry; the type of wood was camphor. The crushing process for the bulk wood was included as part of the preparation of the material. The crushed wood was then sieved into a size 25 mesh and dried so that the moisture content was below 10%. 200 grams of raw material was fed into the reactor. A digital scale with 0.001 g of accuracy was used to weigh the materials. The feedstock from camphor wood is presented in Figure 1.

Figure 1 Camphor wood as feedstock

## 2.2. Experimental Setup

A laboratory scale of a tubular fixed-bed reactor with a base material of *stainless steel* (SUS) 316L was constructed. Figure 2 shows an experimental setup for the investigation of the influence of vapor temperature in the reaction zone on producing liquid. The volume of the reactor was 1.065 $cm^3$. The reactor was equipped with an electric heater installed in the system. A PID controller was connected to the heater system to control the decomposition temperature in the pyrolysis process. The process was conducted without sweeping gas in this experiment. A voltage regulator was installed to supply electrical energy to the heater and to control the heating rate of the process. The reactor was insulated with calcium silicate in order to reduce the heat loss from the wall of the reactor to the surrounding air. To condense the hot vapor, which flows from the reaction zone, a double pipe of the heat exchanger as an LCS was equipped within the system and cooling water at an ambient temperature was circulated through the LCS. The double pipe of the condenser was easier to control than the operational temperature of the LCS (Abdullah et al., 2017). The mass flow rate of the cooling water remained at 0.28 kg/s.

An electric heater was also mounted at the reaction zone to vary the vapor temperature and a PID controller was connected to this heater. A temperature sensor was installed on the outside wall of the reaction zone as a reference temperature for the PID. A voltage regulator was connected to the reaction zone heater to limit the heating supply to the heater. Type K thermocouples were installed at several points to capture the temperature conditions in the process. All of the thermocouples and sensor tools connected to the data acquisition system (DaQ) and the data were captured real-time and stored in the computer.




| | |
|---|---|
| $T_1$ | Liquid temperature |
| $T_2$ | NCG Temperature |
| $T_3$ | Reaction zone temparature |
| $T_4$ | Feedstock temperature |
| $T_5$ | Inside wall temperature |
| $T_6$ | Inlet condenser temeprature |
| $T_7$ | Coling water inlet |
| $T_8$ | Coling water outlet |
| $T_9$ | Ambient temperature |

Figure 2 Experimental setup for investigating the influence of vapor temperature in the reaction zone for producing liquid

### 2.3. Experimental Variation

The operating parameter in this experiment, based on previous research, maintained the reaction temperature at 500°C due to the maximum liquid yield being produced between the temperature range 400-600°C (Chen et al., 2016; Garg et al., 2016). The voltage regulator controls the electric supply to the heater. The variation of the electricity supplied to the heater is 1000, 1500, and 2000 Watts. This variation of power results in the heating rate of the feedstock increasing from 2 to 17°C/minute. The temperature in the reaction zone ranges from 30°C (heater off), 100°C, 150°C, and 200°C. The higher temperature results in a secondary decomposition reaction (Ly et al., 2015), which affects the heating rate due to the additional heat in the reaction zone. The cooling water at an ambient temperature is supplied to the condenser. In the condenser, the heat of the hot vapor is absorbed and then the vapor changes into a liquid.

The vapor with a boiling point below the ambient temperature becomes a *non-condensable gas* (NCG) and is released into the atmosphere. Subtracting the total mass of the feedstock by the mass of the liquid and char can calculate the mass of the NCG. The liquid yield was measured by dividing the mass of the liquid by the total feedstock, based on the following equations (Ly et al., 2016).

$$Liquid\ yield\ (\%) = \frac{Liquid\ weight}{Feed\ weight}\ x\ 100\% \tag{1}$$

$$Solid\ yield\ (\%) = \frac{Solid\ Weight}{Feed\ weight}\ x\ 100\% \tag{2}$$

$$Ash\ yield\ (\%) = \frac{Liquid\ weight}{Feed\ weight}\ x\ 100\% \tag{3}$$

The maximum liquid yield was the primary concern of this research. The temperature of the wall in the reaction zone was investigated to calculate the effect of the reactor temperature on the liquid yield.

## 3. RESULTS AND DISCUSSION

### 3.1. Product Yield

The product’s yield of bio-oil was affected by the vapor temperature in the reaction zone. Controlling the wall temperature reduced the heat loss from the vapor to the system, especially in the reaction zone. The temperature of vapor in this area influenced the liquid yield of the pyrolysis process. A low vapor temperature resulted in early condensation on the wall of the reactor, in the reaction zone, and on the reactor head. Because of the high boiling point of the vapor, it condensed early when the temperature dropped immediately at the wall or the head of the reactor. Table 1 shows the product yield based on the wall temperature of the reaction zone.

The maximum liquid yield of 46% occurred when the reaction zone wall temperature was 200°C and the heating supply to the reactor was at 1500 Watts. The liquid yield produced was influenced by the reaction zone temperature. The liquid yield increased when the temperature of the reaction zone increased. At the low heating rate, the liquid product was significantly increased from 26.5 wt% to 39 wt% until reaction zone wall reached a temperature of 150°C. Meanwhile, the liquid yield slightly increased above that temperature. The increasing of the liquid yield was smaller at the higher heating rate. The vapor temperature in the reaction zone influenced the partial pressure of the vapor. This pressure was needed to transport the vapor to the LCS. Higher temperatures increased the partial pressure. At the low heating rate, the vapor temperature was slightly lower, and it lowered the partial pressure. At the higher heating rate, the vapor temperature was relatively higher and increased the partial pressure. Figure 3 shows the influence of the reaction zone temperature on the liquid yield. Figure 4 shows the comparison of the entire pyrolysis product that was influenced by reaction zone temperature.

Table 1 Product yield due to the wall temperature of the reaction zone

| Reactor Heating Supply (Watt) | Heating rate (°C /minute) | Reaction Zone Wall temperature (°C) | Product Yield (wt%) | | |
|---|---|---|---|---|---|
| | | | Liquid | NCG | Char |
| 1000 | 2.00 | 30 (heater off) | 26.50 | 18.00 | 55.50 |
| 1000 | 2.50 | 100 | 34.50 | 12.50 | 53.00 |
| 1000 | 3.00 | 150 | 39.00 | 13.00 | 48.00 |
| 1000 | 4.00 | 200 | 39.00 | 17.00 | 44.00 |
| 1500 | 5.50 | 30 (heater off) | 38.00 | 19.00 | 43.00 |
| 1500 | 6.50 | 100 | 40.00 | 22.50 | 37.50 |
| 1500 | 7.00 | 150 | 44.00 | 17.00 | 39.00 |
| 1500 | 8.00 | 200 | 46.00 | 21.50 | 32.50 |
| 2000 | 9.00 | 30 (heater off) | 37.00 | 26.50 | 36.50 |
| 2000 | 13.00 | 100 | 41.00 | 24.00 | 35.00 |
| 2000 | 16.00 | 150 | 42.50 | 23.50 | 34.00 |
| 2000 | 17.00 | 200 | 43.50 | 24.00 | 32.50 |

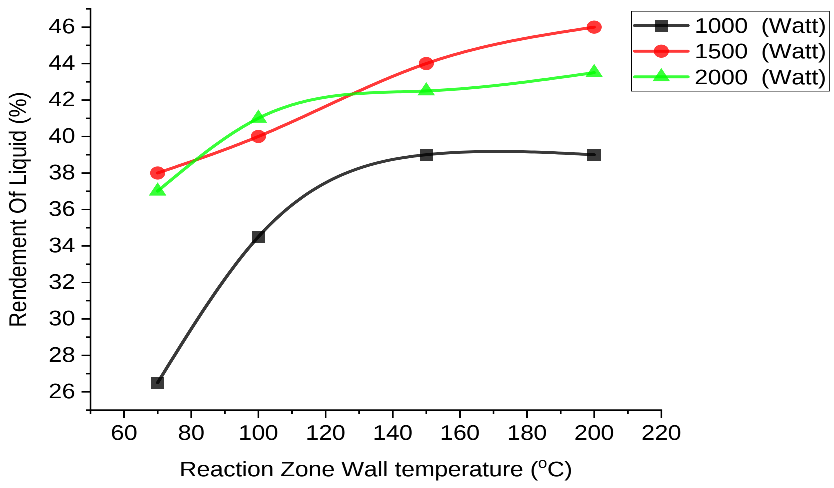



Figure 3 The influence of the reaction zone wall temperature on the liquid yield

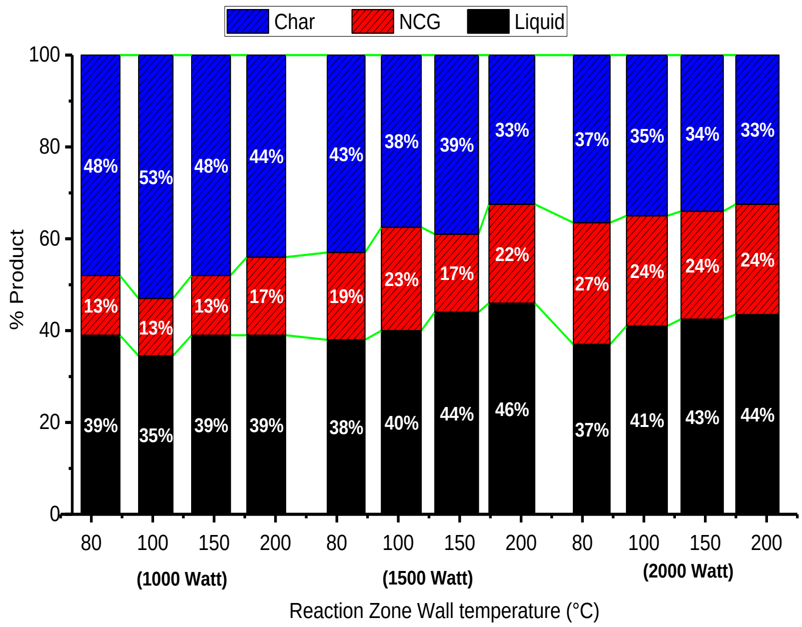



Figure 4 Total pyrolysis product affected by the wall temperature of the reaction zone

Figure 5 shows the temperature distribution in the pyrolysis while the experiment was running. Figures 5a and 5b show the temperature distribution of the 1000-Watt heating supply. Figure 5a depicts the reaction zone with an uncontrolled wall temperature (ambient temperature), in which no heating was supplied to the reaction zone from the outside. The temperatures of the vapor are purely from the decomposition process. Meanwhile, in Figure 5b, the wall temperature of the reaction zone was controlled by the heater and PID at a temperature of 200°C. Figures 5c and 5d illustrate the temperature distribution with a 1500-Watt heating supply, while Figures 5e and 5f show the results for a 2000-Watt heating supply.

The lowest temperature of the vapor in the reaction zone occurred at 1000 Watt and an uncontrolled wall temperature. At the beginning of the process, the vapor temperature rose slowly and led to early condensation in the reaction zone, which is indicated by the temperature drop at the wall inside of the reactor. With the 1500- and 2000-Watt heating supplies, a temperature drop also occurred inside the wall of the reactor. Meanwhile, when the wall temperature in the reaction zone was controlled, the vapor temperature rose at beginning of the process and prevented the vapor from condensing early, increasing the amount of liquid product. But Figure 5f shows that the early condensation still occurred, which was caused by the high boiling point of a vapor compound that was produced by the decomposition process due to the heating rate. This heating rate influenced the decomposition process and the composition of the liquid product (Onay et al., 2001; Şensöz et al., 2006; Uzun et al., 2006; Pütün et al., 2007; Hassen-Trabelsi et al., 2014).

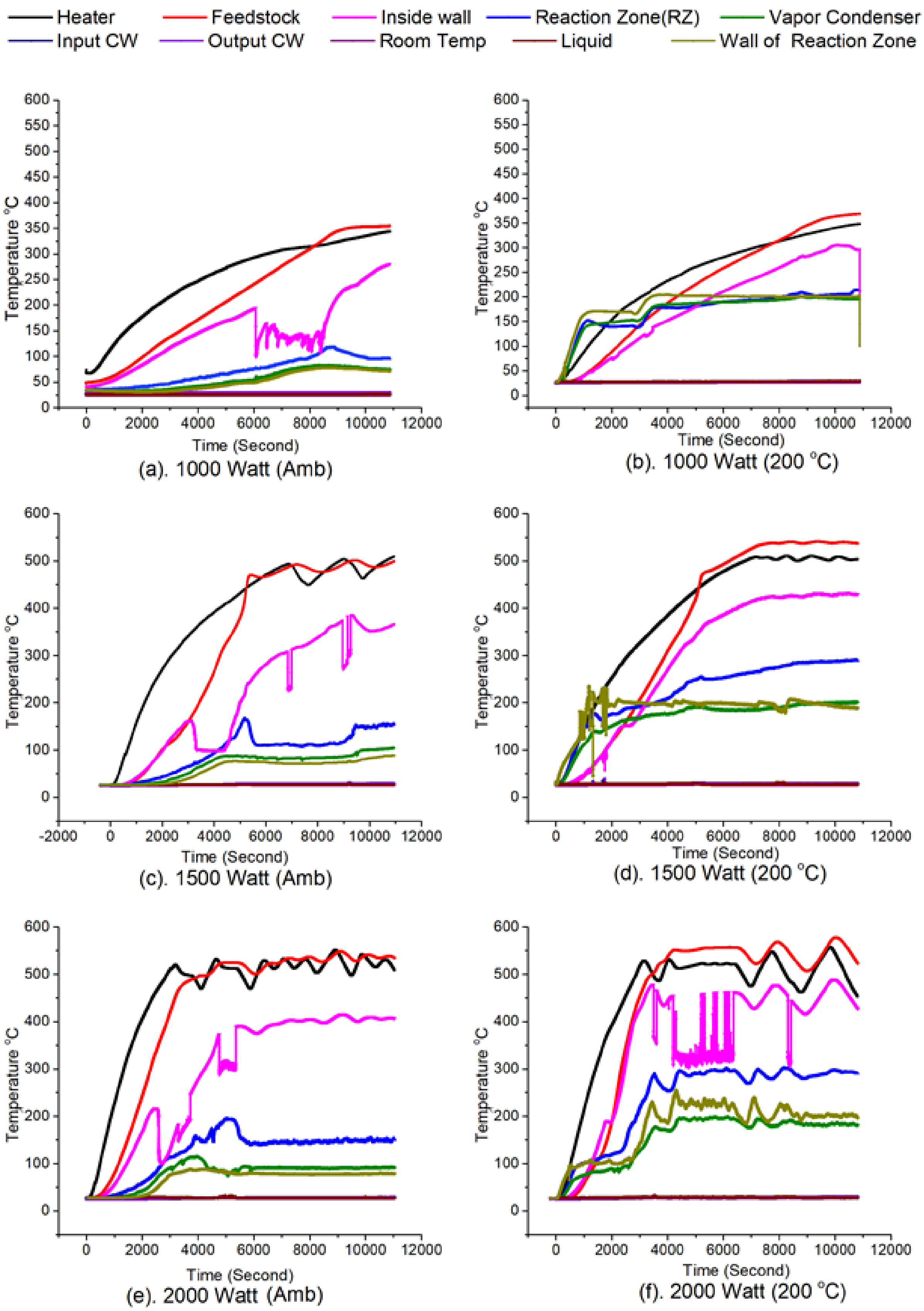



Figure 5 Temperature distribution for the pyrolysis process according to the temperature controllers in the reaction zone

## 4. CONCLUSION

The influence of the temperature in the reaction zone on the liquid produced has been investigated for a non-sweeping gas fixed-bed reactor that used camphor as the feedstock. With a 1000-Watt reactor heating supply, increasing the wall temperature up to 200°C caused a 12.5 wt% increase in the liquid yield. For a 1500-Watt reactor heating supply, increasing the wall temperature up to 200°C caused a 5 wt% increase in the liquid yield and a 4.5 wt% increase occurred with a 2000-Watt heating supply. The lower product yield at a low heating rate and at uncontrolled surface temperature was influenced by the low vapor temperature in the reaction zone. The highest liquid yield of 46 wt% was obtained with a 1500-Watt heating supply and when the wall temperature was 200°C in the reaction zone. Because of its high boiling point, the vapor condensed early on the wall of the reactor when the vapor was at a low temperature.

## 5. ACKNOWLEDGEMENT

The authors wanted to express gratitude to DRPM Universitas Indonesia and Kemenristek Dikti for funding this research through the "Hibah PTUPT" scheme.

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