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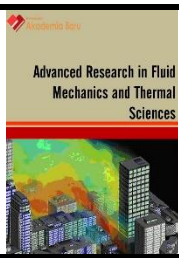

Empirical Modelling of Einstein Absorption Refrigeration System

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ABSTRACT

A single pressure absorption refrigeration system was invented by Albert Einstein and Leo Szilard nearly ninety-year-old. The system is attractive as it has no mechanical moving parts and can be driven by heat alone. However, the related literature and work done on this refrigeration system is scarce. Previous researchers analysed the refrigeration system theoretically, both the system pressure and component temperatures were fixed merely by assumption of ideal condition. These values somehow have never been verified by experimental result. In this paper, empirical models were proposed and developed to estimate the system pressure, the generator temperature and the partial pressure of butane in the evaporator. These values are important to predict the system operation and the evaporator temperature. The empirical models were verified by experimental results of five experimental settings where the power input to generator and bubble pump were varied. The error for the estimation of the system pressure, generator temperature and partial pressure of butane in evaporator are ranged 0.89-6.76%, 0.23-2.68% and 0.28-2.30%, respectively. In addition, all the estimated generator temperatures and partial pressures of butane are within the error bar range that derived from the standard deviation of the experimental results.

Keywords:
Absorption refrigeration; empirical modelling; system pressure; generator temperature; partial pressure

1. Introduction

The ninety-year-old single pressure absorption refrigeration system invented by Albert Einstein and Leo Szilard is attractive as it has no mechanical moving parts and can be driven by heat alone. However, the literature on either the refrigeration system or its components is scarce. Almost no work was done on this refrigeration system for nearly five decades after its invention. Follin *et al.,* [1,2] intended to operate the refrigerator at temperatures of 65°C or below, which could be harvested from heat sources such as geothermal, solar thermal collectors, or cogeneration systems.

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In their study, the theoretical coefficient of performance (COP) of the system is in the range between 0.20 and 0.25. However, no further works of these studies are found.

In 1997, Delano [3] analysed an Einstein-Szilard refrigeration system without bubble pump using a model derived from the principles of mass and energy conservation. The COP of the system is 0.35. A year later, he applied the Patel-Teja equation of state (EoS) to assess the energy content of the substances and mixtures in each component of a complete refrigeration system [4]. He derived an analytical model to estimate the mass flow rate of the bubble pump. For a 4 bar system, when the temperatures of the evaporator, condenser and generator were –7°C, 43°C, and 102°C, respectively, the theoretical COP was 0.17. He built a working prototype of the refrigeration system. This prototype operated with isobutane, ammonia, and water. Heat input to the generator and bubble pump of the prototype were 150–250 W and 50–70 W, respectively. The evaporator temperature dropped to –2°C when the condenser temperature was maintained at 21°C using tap water. However, no further results, information, or publications on this prototype. Shelton *et al.,* [5] presented the design analysis of Delano's refrigeration system where they introduce a prototype, but only the working conditions of the prototype were mentioned. In another paper, Shelton *et al.,* [6] reported their studies on the refrigeration system using the second law of thermodynamics.

In year 2000, Schaefer [7] converted the Einstein refrigeration system into a heat pump. She estimated properties of the working fluids with EoS and evaluated the performance of the system using the mass and energy conservation equations. Three pairs of temperature of the condenser and evaporator were studied. The COPs for these studied pairs were 1.51, 1.88, and 1.76, respectively. Several triplets of working fluids were investigated theoretically. The triplet of water-ammonia-butane has the highest COP of 1.88 at 5.25 bar. Despite the thorough analysis of the cycle, she did not build or test with any prototype.

Mejbri *et al.,* [8] investigated the feasibility of the Einstein refrigeration system. Two modified configurations were evaluated using Delano's analytical model. In addition, Delano's vapor-liquid ratio was used to estimate the mass flow rates of the system. The theoretical COP of the system was 0.18. However, the vapor-liquid ratio in Delano's study was derived from an air-lift pump model and the model was verified by using water only [4]. These assumptions are inaccurate as the ammonia has great impact to the performance of bubble pump [9]. Furthermore, Delano's vapor-liquid ratio was obtained from a 4 bar system rather than Mejbri's 5 bar system. As the pressure changes, the ratio will change accordingly due to the variation in boiling point.

Researchers from University of Shanghai for Science and Technology, China has published seven Chinese journal papers related to the Einstein refrigeration system and bubble pump [10-13,14-16]. Wang *et al.,* [11] presented a method to assess the system, they created measurement parameters for the components on a LabVIEW platform to analyze the system at different conditions. The design parameters for the evaporator, condenser, and bubble pump of the refrigeration system were presented [12]. No further experimental work or images were found though they mentioned 'the prototype' many times in their papers. In addition, they presented information that is very similar to Delano's studies.

Papers that studied bubble pumps that used in Einstein refrigeration system or other vapour absorption refrigeration systems are relatively common compared to the investigation of Einstein refrigeration system alone. Researchers from University of Windsor, Canada modelled and analysed the performance of bubble pump for a vapour absorption refrigeration system [17-19]. Lin *et al.,* [20] from Institute of Refrigeration Technology, China, studied the bubble pump with the configuration of multiple tubes.

As there are no mechanical moving parts, such as pump and compressor (to control the pressure), the pressure of the system is highly relied on the heat input to the components. In all the previous studies, both the system pressure and component temperatures that fixed by the researchers were merely based on the assumption of ideal condition. These values somehow have never been verified by any experimental results. Several issues that were not considered have caused the assumptions invalid for practical condition. In this paper, new empirical modelling was developed based on experimental data to estimate the system pressure, generator temperature and partial pressure of butane in evaporator. These parameters are important to estimate the temperature in the evaporator. The empirical modelling was verified by five experimental settings where the power input to generator and bubble pump were varied.

2. Methodology

One experimental rig as shown in Figure 1 was set up. The Einstein refrigeration consists of five main components, namely generator, condenser, evaporator, tank and bubble pump. Three working fluids used in this system are butane as the refrigerant, water as the absorbent and ammonia as inert gas or also known as pressure equalizing gas. The ammonia vapour from generator (1) is channeled into the liquid butane in the evaporator to reduce the partial pressure of the butane. As the partial pressure of butane reduce, the butane evaporates and cools itself and its surroundings. The vapour mixture of ammonia-butane (2) enters the condenser, the ammonia is absorbed by the water (6) from the tank due to gravity. As the ammonia is absorbed by the water, partial pressure of butane is restored, then the butane condenses into liquid form at room temperature. Ammonia solution is heavier than liquid butane, hence, two layers of liquid are formed in condenser. The ammonia solution flows to generator (4) is heated up to separate the ammonia from water. The water (weak ammonia solution) is then pumped into the tank (5) through a bubble pump.

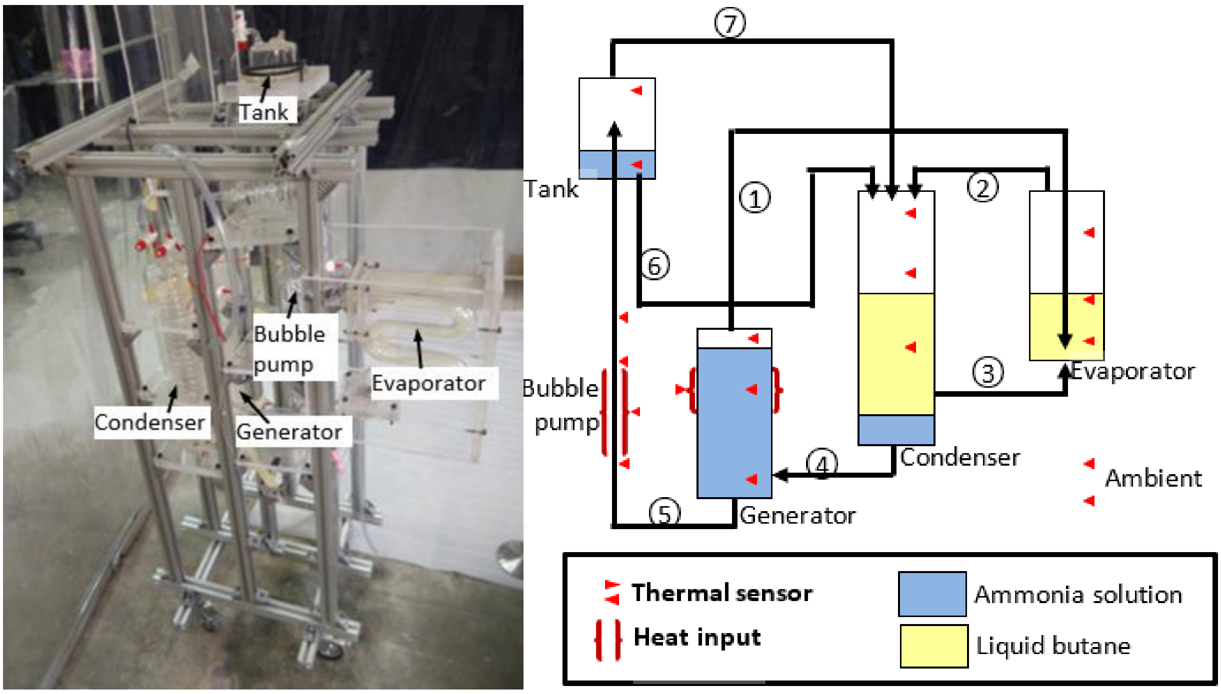


Fig. 1. Description of the experimental setup

The components are mainly made of borosilicate glass, and these components are clamped and supported by acrylic plates. All chambers are fixed on an aluminum frame and are connected using polytetrafluoroethylene (PTFE) and nylon tubes. All the chambers are equipped with N-type thermocouples (TC), and the temperatures are logged through TC-08 data loggers. The generator and bubble pump are heated up using a 500W stainless steel heater coil separately. The heaters are controlled by two 240 V Variacs (autotransformers). Their energy use is logged using two multimeters through a PC interface. The system was evacuated using vacuum pump before it was charged with butane and ammonia solution. Liquid Butane and Ammonia solution of 25% concentration were charged into the system according to the description of Chan and McCulloch [21]. The voltage input to both the generator and bubble pump was fixed at 75-95 V. However, the heat input to the generator and bubble pump varies between 50 W and 85 W, and between 65W and 115W, respectively.

2.1 Modelling of the System

Empirical model was developed and used with the thermodynamic models to analyse the system performance. The empirical model is used to estimate its operating conditions such as the system pressure and temperatures of the components. Meanwhile, the thermodynamic models are used to estimate mass flow rates between the components. When Delano [4] and Mejbri *et al.,* [8] analysed the refrigeration system theoretically, the system pressure and temperatures that fixed by them were based on the assumption of ideal condition. These values somehow have never been verified by any experimental results. Several issues that were not considered have caused the assumptions invalid for practical condition. For instance, the system pressure was determined based on the desired condensation temperature of butane at ambient temperature rather than the heat input to the generator and bubble pump. The ammonia vapour generated by the generator and bubble pump will affect the system pressure directly. Hence, the system pressure correlation is proposed as the following:

$$P_{sys} = \dot{Q}_{gen}\left(0.0772 - 0.0002\dot{Q}_{gen}\right) - \left(0.0002\dot{Q}_{bp}\right) \tag{1}$$

where the P_{sys} is the estimated system pressure, $\dot{Q}_{gen}$ is the fixed heat input generator, and $\dot{Q}_{bp}$ is the fixed heat input to the bubble pump. In addition, the temperature of the generator was fixed at 102°C and 130°C by Delano [4] and Mejbri *et al.,* [8], respectively. Delano wanted to obtain the desired vapour composition from the generator, meanwhile, Mejbri *et al.,* [8] wanted to power the refrigeration system using solar collector at 130°C. However, the generator temperature is influenced by the heat input to the generator. Hence, the generator temperature can be estimated from:

$$T_{gen} = \dot{Q}_{gen}(2.0739 - 0.011\dot{Q}_{gen}) \tag{2}$$

where the T_{gen} is the estimated generator temperature, and $\dot{Q}_{gen}$ is the fixed heat input generator. Delano [4] and Mejbri *et al.,* [8] obtained the evaporator temperature through the three-phase equilibrium calculations. The ammonia vapour is introduced to the evaporator as the inert gas to reduce the partial pressure of butane. Although there is a small amount of dissolved ammonia in butane, the evaporation process mainly happens on the liquid butane. Hence, the evaporator temperature is the saturation temperature of butane at its partial pressure. The partial pressure of the butane can be estimated through the following correlation:

$$P_b = (0.1874{P_{sys}}^2 - 1.7471P_{sys} + 5.5414)\left[1 - \left(\frac{1-\frac{\dot{Q}_{bp}}{89}}{8}\right)\right] \tag{3}$$

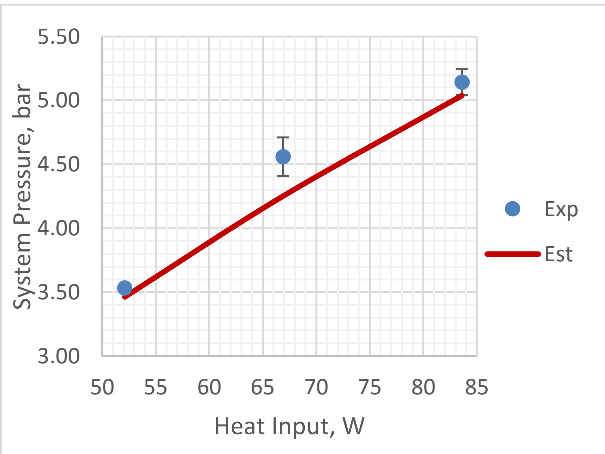
where the P_b is the estimated partial pressure in evaporator, P_{sys} is the estimated system pressure, and $\dot{Q}_{bp}$ is the fixed heat input to the bubble pump.

3. Results and Discussion

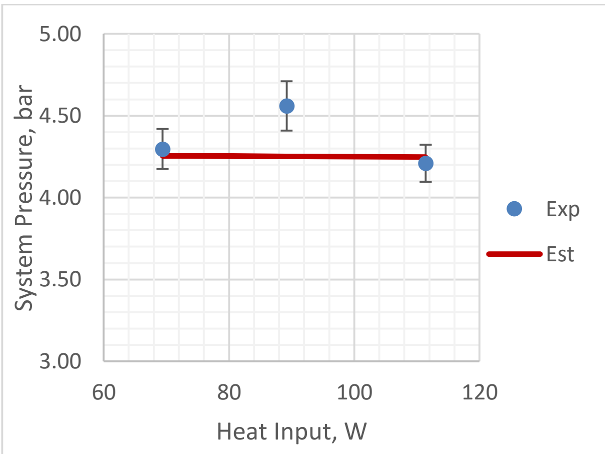
As the voltage input to both the generator and bubble pump was fixed at between 75 V and 95 V, the heat input to the generator and bubble pump varies between 50 W and 85 W, and between 65W and 115W, respectively. Two sets of experiment were conducted, wherein for the first experiment, the voltage to the bubble pump was fixed at 85 V (approximately 89 W), and the voltage to the generator was fixed at 75 V (approximately 53 W), 85V (approximately 67 W), and 95 V (approximately 84 W). In the second experiment, the voltage to the generator was also fixed at 85 V (approximately 67 W), and the voltage to the bubble pump was fixed at 75 V (approximately 69 W), 85V (approximately 89 W), and 95 V (approximately 111 W).

3.1 Estimation of System Pressure

The estimates of the system pressure for different heat input to the generator and bubble pump are shown in Figure 2. Figure 2(a) shows the estimates of the system pressure when the heat input to the generator is varied at fixed bubble pump heat input. When the heat input to generator increases, the system pressure increases also. This might due to the increase of ammonia vapour generated from the generator, but the water from the tank is not sufficient to absorb all the generated ammonia vapour. Meanwhile, Figure 2(b) shows the estimates of the system pressure when the heat input to the bubble pump is varied at fixed generator heat input. In spite of the increase of heat input to bubble pump, the system pressure fluctuates between 4.2 and 4.6 bar. This might due to the heat input to the bubble pump is mainly used as an energy source to transport the water to the higher tank, instead of increase the water vapour volume in the system. Because the water vapour condenses into liquid during pump process [9]. As shown in Table 1, the error range is between 0.89% (when heat input to bubble pump and generator is 111.4 W and 66.9) and 6.76% (when the heat input to bubble pump and generator is 89.2 W and 66.9 W). This error is acceptable as it is below 10%.



(a)



(b)

Fig. 2. Estimation of the system pressure: (a) heat input to bubble pump is fixed, (b) heat input to generator is fixed

Table 1
System Pressure

Heat Input, W Bubble Pump	 Generator	Pressure, bar Experimental (average)	 Estimation	Error, %
89.20	52.1	3.53	3.46	2.04
89.20	66.9	4.56	4.25	6.76
89.20	83.6	5.14	5.04	2.04
69.40	66.9	4.30	4.26	0.95
111.40	66.9	4.21	4.25	0.89

3.2 Estimation of Generator Temperature

The estimates of the generator temperature for different heat input to the generator and bubble pump are shown in Figure 3. Figure 3(a) shows the estimates of the generator temperature when the heat input to the generator is varied at fixed bubble pump heat input. When the heat input to generator increases, the generator temperature increases. Meanwhile, Figure 3(b) shows the estimates of the generator temperature when the heat input to the bubble pump is varied at fixed generator heat input. In spite of the increase of heat input to bubble pump, the generator temperature fluctuate between 84 and 92 °C. As shown in Table 2, the lowest error is 0.23% when the heat input to bubble pump and generator is 89.2 W and 83.6 W, respectively. While the highest error is 2.68% when the heat input to bubble pump and generator is 111.4 W and 66.9 W, respectively. Worth mentioning, all the estimated generator temperatures are within the error bar range that derived from the standard deviation of the experimental results.

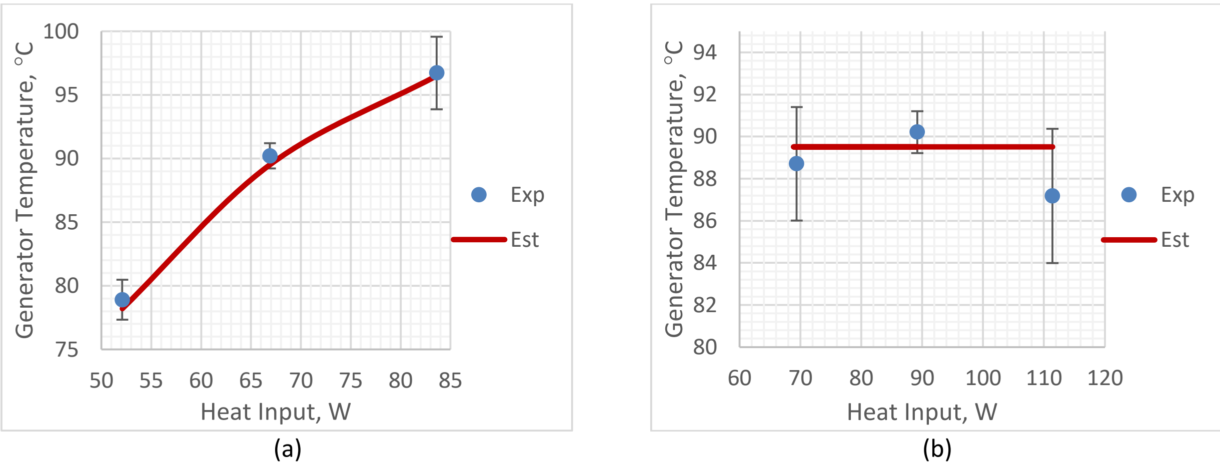


Fig. 3. Estimation of the generator temperature: (a) heat input to bubble pump is fixed, (b) heat input to generator is fixed

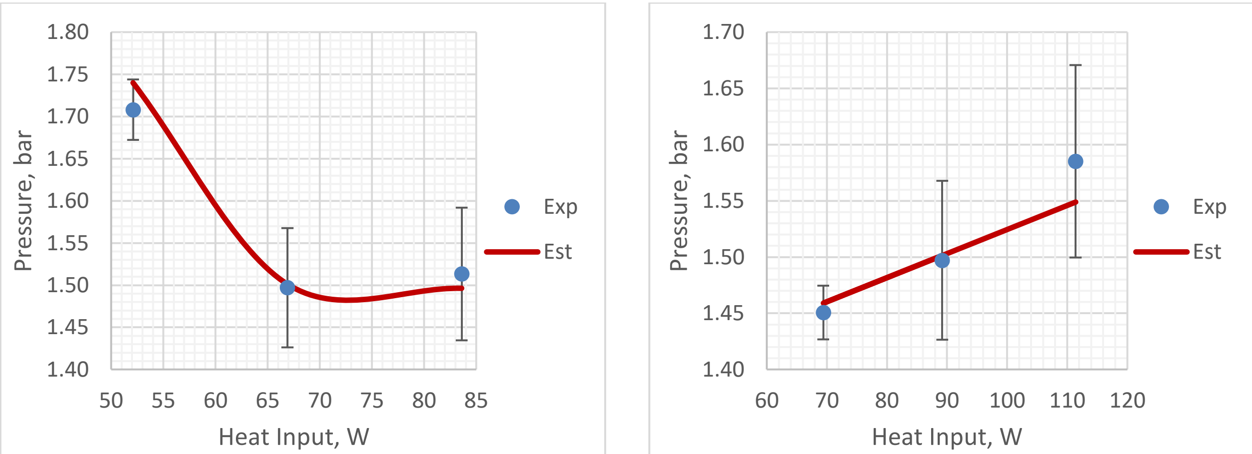
Table 2
Generator Temperature

Heat Input, W Bubble Pump	 Generator	Temperature, °C Experimental (average)	 Estimation	Error, %
89.20	52.1	78.90	78.19	0.90
89.20	66.9	90.21	89.51	0.77
89.20	83.6	96.73	96.50	0.23
69.40	66.9	88.71	89.51	0.90
111.40	66.9	87.18	89.51	2.68

3.3 Partial Pressure of Butane (in Evaporator)

The estimates of the partial pressure of butane in the evaporator for different heat input to the generator and bubble pump are shown in Figure 4. Figure 4(a) shows the estimates of the partial pressure of butane when the heat input to the generator is varied at fixed bubble pump heat input. When the heat input to generator increases, the amount of ammonia vapour bubbled in the evaporator increases also. This causes the partial pressure of butane in the evaporator reduces. Meanwhile, Figure 4(b) shows the estimates of the partial pressure of butane when the heat input to the bubble pump is varied at fixed generator heat input. When the heat input to the bubble pump increases, the amount of water pumped to the higher tank increases also. In other words, the amount of ammonia vapour in the system reduces due to the absorption of ammonia vapour into water. As a result, the impact of ammonia vapour to the partial pressure of the butane reduces as the amount of ammonia vapour reduces.

As shown in Table 3, the lowest error is 0.28% when the heat input to bubble pump and generator is 89.2 W and 66.9 W, respectively. While the highest error is 2.30% when the heat input to bubble pump and generator is 111.4 W and 66.9 W, respectively. Similar to the estimation of generator temperature, all the estimated partial pressure of butane is within the error bar range, which is derived from the standard deviation of the experimental results.



(a) (b)

Fig. 4. Estimation of the partial pressure of butane in evaporator: (a) heat input to bubble pump is fixed, (b) heat input to generator is fixed

Table 3
Partial Pressure of Butane

Heat Input, W		Pressure, bar		Error, %
Bubble Pump	Generator	Experimental (average)	Estimation	
89.20	52.1	1.71	1.74	1.86
89.20	66.9	1.50	1.50	0.28
89.20	83.6	1.51	1.50	1.11
69.40	66.9	1.45	1.46	0.56
111.40	66.9	1.59	1.55	2.30

4. Conclusions

Einstein refrigeration system was invented by Albert Einstein and Leo Szilard nearly ninety year ago. The system is attractive as it has no mechanical moving parts and can be driven by heat alone. However, the literature that related to this refrigeration system is scarce. In previous studies, the refrigeration system was analysed theoretically, both the system pressure and temperatures were fixed by the assumption of ideal condition. These values somehow have never been verified by any experimental results. Several issues that were not considered have caused the assumptions invalid for practical condition. Empirical models were proposed and developed in this paper to estimate the system pressure, generator temperature and partial pressure of butane in evaporator. These parameters are important to estimate the operation of the system and the temperature of evaporator. These empirical models were verified by five experimental settings where the power input to generator and bubble pump were varied. Error for each model was calculated based on the experimental results. The error for the estimation of the system pressure, generator temperature and partial pressure of butane in evaporator are ranged 0.89-6.76%, 0.23-2.68% and 0.28-2.30%, respectively. In addition, all the estimated generator temperatures and partial pressure of butane are within the error bar range that derived from the standard deviation of the experimental results.

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