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Optimisation of Energy Usage in Ceramic Kiln Using Pinch Technique

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The Pinch technology is one of the most advanced methodologies for energy saving in processes and total sites based on thermodynamic principles. In ceramic industry, energy distribution in kiln is very complex. The pinch analysis was used to minimise energy levels for ceramic kiln during operation at Phuoc Du Long ceramic company in Vietnam. Using Pinch technology, it was possible to identify appropriate changes in the core process conditions that could have an impact on energy savings. After the heat and material balance was established, targets for energy saving could be set prior to the design of the heat exchanger network in ceramic kiln. The results showed that the efficiency of the heat exchanger in the flue heat exchanger network had been determined. This also indicated that at the optimisation conditions, the heat loss was at a minimum. The heat and material balance were established in ceramic kiln. From the basic heat and material balance inside the old type of ceramic kiln, the energy lost via flue gas emission and heat transfer was found to be about 600 kJ. The Pinch point at 820 °C was determined to give a chance for energy saving.

1. Introduction

Ceramic industry is a traditional industry of Vietnam with more than 1,000 companies distributed throughout the country. The ceramic manufacturing process consisted of various stages which differ as a function of the product made. The main production stages are raw materials preparation, forming, drying, glazing and decorating, and firing (Bovea et al., 2010).The ceramic manufacturing process requires high energy consumption, principally thermal energy. The greatest thermal energy is used to fire product in ceramic kiln and accounts for 55 % of all used thermal energy in the manufacturing process (Monfort et al., 2010). Thermal energy costs usually take about 15 % of total ceramic tile manufacturing costs. Normally, the CO_2 emissions produced by material combustion in ceramic manufacturing is estimated to be about 265 kg CO_2/t product. In the manufacturing process, the emission from burning fuel accounts for about 90 % of all CO_2 emission. The other emissions from decomposition, and firing of the calcium and/or magnesium carbonates present in the product makes up about 10 % of all CO_2 emissions in the process (Mezquita et al., 2014). Reducing kiln energy consumption would lead to decreasing energy costs and CO_2 emissions.
Although the Pinch Technology was created in the last century, the theory of this method still has been developing in recent years. Bandyopadhyay (2013) published the study in a chapter “Applications of Pinch Analysis in the Design of Isolated Energy Systems” in the Handbook of Process Integration. In the research, the Pinch Analysis was conducted to design the isolated energy systems (Bandyopadhyay, 2013). Another researcher has reviewed the theoretical foundations of the Pinch Technique in a chapter of the book “Computer Aided Chemical Engineering”. In this book, the authors showed the principle to analyse of the process for saving energy (Dimian et al., 2014). Winterbone and Turan (2015) published a chapter “Pinch technology” in a book “Advanced Thermodynamics for Engineers”. The study was to consider all the heat transfer occurring in a large energy utilising facility, the best way to make the energy transfer inside the plant, and the overall operating costs to be minimised (Winterbone and Turan, 2015).
Pinch Analysis is known as a method to minimise the energy costs in the chemical process by recovering heat energy in the production process. This approach is to increase the thermodynamic efficiency of the network and to reduce the cost of utilities. By adjusting the minimum approach distance, the ideal minimum utility requirements and the total surface area of heat exchanger network is to be balanced. One of the research

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groups following this way was Binosi and Papavassiliou (2009) from Italy and Spain. Their study focused on the definition and measurement of gauge-invariant off-shell form-factors, and gauge-invariant definition of basic electroweak parameters (Binosi and Papavassiliou, 2009). Fujimoto et al. (2011) published the study "Pinch analysis for bioethanol production process from lignocellulosic biomass". In that research, mass and heat balances were obtained by process simulations, and the heat recovery ratio was determined by pinch analysis. The results were very interesting as 38 % of energy saving was achieved. They also recognised that the energy supply and demand were not effectively utilised in the range of temperature from 95 to 100 °C. The energy required for the process could be supplied by heat released during the process (Fujimoto et al., 2011). In the year 2015, a group of researchers from Spain and Romania had presented the study of "Process intensification in biodiesel production with energy reduction by pinch analysis". The study was conducted on the overall process of biodiesel synthesis from vegetable oil and methanol. The Pinch Analysis was used to calculate the minimum energy requirements of alternative processes (Pleşu et al., 2015). In the research of "Cost optimal energy sector planning: a Pinch Analysis approach" the renewable energy sources was used as the alternative material to reduce cost of energy and to contribute to the reduction of greenhouse gas emissions and pollutants (Bandyopadhyay and Desai, 2016). In the research of Jia et al. (2016), the "Multi-dimensional pinch analysis for sustainable power generation sector planning in China" was published. The study considered five key indices: carbon footprint, energy return on investment, water footprint, land footprint, and risk to humans (Jia et al., 2016). The expanding of the utility targeting procedure in the pinch method for heat exchanger network synthesis were presented in the research by Priya and Bandyopadhyay (2017) via the paper "Multiple objectives Pinch Analysis". In their study, the Multiple Objectives Pinch Analysis (MOPA) was used to consider the cost and quality of different resources. The proposed methodology could be applied to analyse the Indian power sector with constraint on emission of carbon dioxide to optimise cost and water footprint of new power plants (Priya and Bandyopadhyay, 2017). In the research "Selection of energy conservation projects through Financial Pinch Analysis" by Roychaudhuri et al. (2017), Pinch technology was also used as an efficient tool for energy and capital cost saving in a chemical plant as mentioned in the researches of energy conservation projects in the pulp and paper and cement industries (Roychaudhuri et al., 2017). Another study about "Optimization of pre-combustion capture for thermal power plants using Pinch Analysis" of Valiani et al. (2017) showed the results that via the Pinch Analysis, they reduced energy waste and fuel flow, they also indicated that power plant efficiency could be increased around 8 % by integrating the hot exhaust gases from the gasification unit with power plant boiler using a heat recovery steam generation (HRSG) unit. With this modification, bagasse consumption was decreased by 23 % (Valiani et al., 2017).

In Vietnam, there have been lots of small ceramic enterprises using the same old type of kiln in their manufacturing process. In the past, the small ceramic enterprises were aggregated as the ceramic villages located across Vietnam. Nowadays, the numbers of ceramic village have been reducing and there are about 1,000 ceramic enterprises still in operation. The ceramic villages that are in operation are Chu Dau in Hai Duong province, Bat Trang in Ha Noi capital, Phu Lang, and Tho Ha in Bac Ninh province, Phuoc Tich in Hue city, Thanh Ha in Quang Nam province, Bau Truc in Binh Thuan province, Cay Mai in Hochiminh city, Bien Hoa in Dong Nai province, Lai Thieu – Tan Phuoc Khanh – Thu Dau Mot in Binh Duong province, and Vinh Long in Vinh Long province. They have been using many types of biomass as the combustible material to fire in the kiln such as wood, rice husk, and saw dust. The problems of these enterprises are old technology, waste energy, and environmental pollution, especially in flue gas emission. In this work, pinch analysis was applied to describe the heat exchange between hot and cold product streams in the ceramic kiln at the Phuoc Du Long ceramic company in Binh Duong province in Vietnam. Pinch Analysis method was used to calculate the thermal capacity of streams and the energy exchange during operation in the ancient ceramic kiln. Energy balance was determined during the operation of ceramic kiln. The results from this research could be applied to other ceramic companies in Vietnam to enhance energy efficiency in the manufacturing process and reducing environmental pollution.

2. Experimental

2.1 Pinch technology

Pinch technology provides a simple methodology for systematically analysing chemical processes and the surrounding utility systems with the help of the First and Second Laws of Thermodynamics. The First Law of Thermodynamics provides the energy equation for calculating the enthalpy changes in the streams passing through a heat exchanger. The Second Law determines the direction of heat flow. In a heat exchanger unit neither can a hot stream be cooled down below cold stream temperature, nor can a cold stream be heated up to a temperature higher than that of the hot stream. In practice, the hot stream is only cooled to a defined temperature by the temperature approach of the heat exchanger. The temperature approach is minimum allowable temperature difference (ΔT_{min}) in the stream temperature profiles for the heat exchanger unit. The temperature level at which ΔT_{min} is to be observed in the process is referred to as pinch point or pinch condition. The pinch defines the minimum driving force allowed in the exchanger unit.

2.2 Ceramic kiln description

Ceramic kiln, a cube shape furnace, has a top slope of 15 - 20 degrees. The dimension of each kiln is 6 m wide, 2 m long and 2 m high. At the bottom of the kiln, there are some holes with dimensions of 0.1 x 0.2 m arrange along the width. In the operation situation, hot stream enters to the kiln via the holes to burn the ceramic (Figure 1). The exhaust air is used to dry ceramic in the next kiln. The energy is supplied to the kiln during the burning stage by the hot stream. The temperature of ceramic kiln is controlled at around 1200 °C in 3 h.

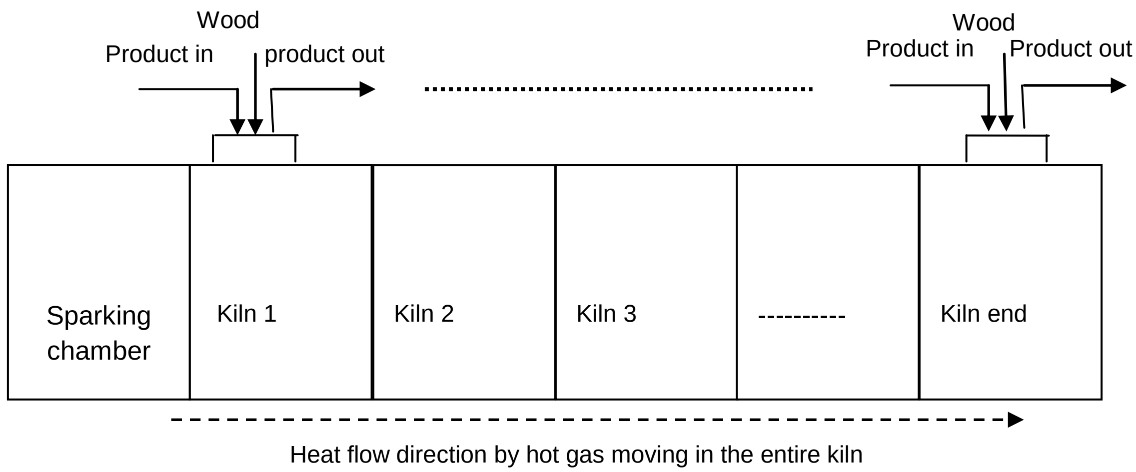

Figure 1: Flow diagram of ceramic kiln

The ceramic products are fed into the individual kiln as a batch feeding by manual. The workers have to set up the products in order to optimise the space inside the kiln. Once the ceramic products are fed into the individual kiln, the worker will start burning the ceramic products. At the beginning, the fire will be ignited in the sparking chamber to heat up and dry the product in kiln 1 and kiln 2. After 3 h, kiln 1 will be changed to firing stage and the temperature is increased up to 1,200 °C in 3 h. Kiln 2 is converted into the heating and drying stage using the hot flue gas from kiln 1. Simultaneously, the product in kiln 3 is set up and prepared for heating and drying stage. When kiln 2 starts firing, kiln 1 becomes the cooling down stage and kiln 3 starts drying and heating up stage in high temperature. The process takes place continuously until the kiln end has finished. In this study, the ceramic products were the vases with the equivalent diameter from 0.1 m to 0.5 m and the height from 0.2 m to 1.2 m depending on types of vase. The rubber wood is cut into similar cylindrical shapes with the diameter of about 0.1 m and 0.4 m length. The air was supplied to the combustion process by the fan.

3. Results and discussion

3.1 Energy balance of ceramic kiln

Figure 2 shows the schematic cross-section of such a ceramic kiln along with the most important parameters Q, the mass flow rate of dry air; T, the temperature of the air; and ϕ, the humidity of the air

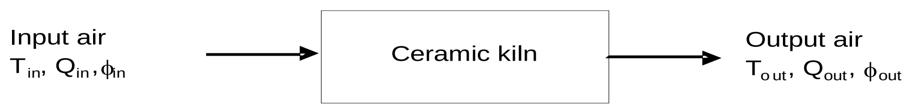

Figure 2: The schematic cross-section of ceramic kiln

Characteristics of the input sources are summarised Table 1. Rubber wood was used as fuel to increase temperature of the dry air and product. Rubber wood is the most popular combustible material used as fuel in the ceramic kiln in the Southeast provinces of Vietnam. Rubber wood contains about 16,000 kJ/kg of calorific value and will release a large amount of energy in the kiln when it burns. This huge amount of energy source is used to heat up the air and ceramic to push the chemical reactions taking place inside the ceramic. The material used to make the ceramic is clay and others inorganic substance with the density of about 2,000 kg/m^3. During the research, the amount of ceramic product was constantly 10 t for each feeding time and exactly the same amount in the other individual kilns. The total volume of air input was fixed at 10,000 m^3 and the weight of rubber wood was 3.6 t for each batch of ceramic. The flue gas emission after exchanging energy to cold air and products was discharged to the atmosphere via the chimney of the kiln.

Table 1: Input material for ceramic kiln at the Phuoc Du Long ceramic company

Input material	Quantity	Properties
Rubber wood	3.6 t	Density: 600 kg/m^3 Calorific value: 16,000 kJ/kg
Dry air	10,000 m^3 (12,000 kg)	Heat capacity: 1 kJ/kg.K
Ceramic	10 t	Water content: 10 % Density: 2,000 kg/m^3 Heat capacity: 4,500 kJ/kg

The energy exchange in the ceramic kiln was calculated using Eq(1) and summarised in Table 2 as follows.

$$Q = m \times q \quad (1)$$

Where: Q – Heat load, kJ;
m – Quantity of material, kg;
q – Calorific value, kJ/kg.

Table 2: Stream data entered the ceramic kiln

Input material	Input source	Source temperature, °C	Target temperature, °C	Heat load, kJ
Rubber wood	Hot air 1	1,500	800	57,600
Dry air	Hot air 2	1,200	30	14,040
Ceramic	Ceramic	30	1,200	45,000
	Water	30	1,200	26,040

In calculation results in Table 2, hot air 1 was 1,500 °C at the inlet, reduced to 800 °C at the outlet, and released 57,600 kJ of energy. Hot air 2 dropped from 1,200 °C to 30 °C and released 14,040 kJ. The ceramic that contained mostly of inorganic substances and water was increased in temperature from 30 °C to 1,200 °C and absorbed 71,040 kJ in total. The difference between released and obtained energy was 600 kJ and is taken into account as heat lost during the firing process taking place.

3.2 Pinch analysis for ceramic kiln

Energy in ceramic kiln was analysed by Pinch Analysis Tool. The input data were used to calculate the thermal capacity of hot and cold streams in the kiln. The difference of temperature in calculation was chosen to be 10 °C. To calculate the thermal capacity for the stream, the mass was multiplied with the specific heat of each stream. The calculation was conducted with all the hot and cold streams using Eq(2) and the results are shown in Table 3.

$$CP = W \times C_P \quad (2)$$

Where: CP – heat capacity, kJ/K
W – Mass, kg
C_P – specific heat, kJ/kg.K

Table 3: Pinch Analysis summary report

ID	Stream	Source temperature, °C	Target temperature, °C	Heat load, kJ	Thermal capacity, kJ/K
1	Hot stream 1	1,500	800	57,600	82.3
2	Cold stream 1	30	1,200	26,040	22.3
3	Hot stream 2	1,200	30	14,040	12.0
4	Cold stream 2	30	1,200	45,000	38.5

The enthalpy is a very important parameter used to calculate energy efficiency. In this study, the changed enthalpy, ΔH, for each stream was determined by multiplying the heat capacity by differential temperature between the source and target temperature. This expression is presented in Eq(3) as follows:

$$\Delta H = CP \times (T_T - T_S) \tag{3}$$

Where: T_T – Target temperature, °C
T_S – Source temperature, °C

The results of calculation are shown in Figure 3. In Figure 3, there are three regions of energy change during the firing of ceramic, they are heating duty, heat recovery, and cooling duty. The heat recovery stage spent the largest amount of energy in the ceramic kiln with the temperature increasing from 100 °C to about 1,200 °C. These results also occurs very often in most of the ceramic plants in Vietnam. The enthalpy of cold stream was gradually increased. The hot stream showed the Pinch point at 820 °C. This means that there is an opportunity to reduce energy consumption in the ceramic kiln using rubber wood as combustion fuel in Vietnam. This resulted in the chances to reduce the cost of production as well.

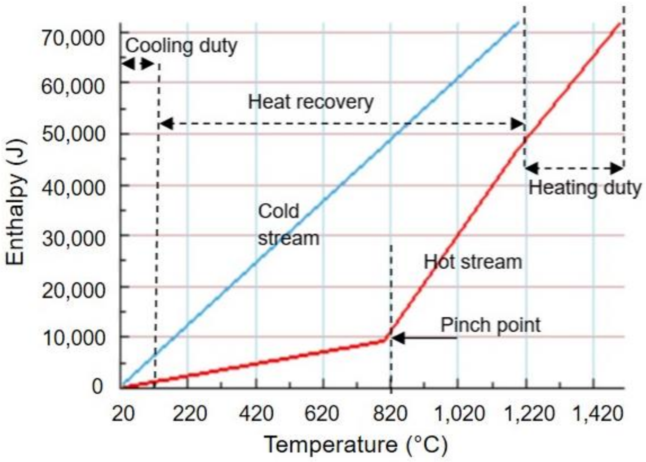

Figure 3: Enthalpy vs. temperature of the hot and cold streams in ceramic kiln

Figure 4 shows that there are two regions of energy exchange comprising of releasing energy and obtaining energy.

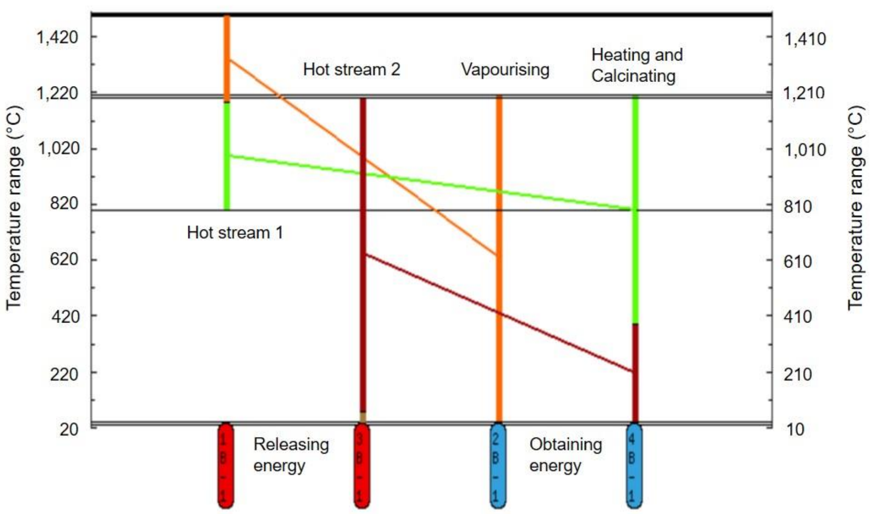

Figure 4: Diagram for energy exchange during operation of ceramic kiln

The energy from hot stream 1 was used to completely evaporate water content in ceramic, and provide energy to calcinate the ceramic. The energy from hot stream 2 was spent to heat up the body of the ceramic product. This means that most of the energy in the kiln was transported into the product. Even so, the hot stream contained higher energy than the demand of firing the product. This created a chance of enhancing energy efficiency in the kiln by optimising the amount of rubber wood used by deriving the hot flue gas through at least 3 individual kilns. This method helped to reduce the amount of rubber wood used to about 200 kg for each individual kiln due to the saving of energy in the heating up, drying stage, and feeding stage.

4. Conclusions

By computational method, the Pinch point for energy exchange in ceramic kiln at the Phuoc Du Long ceramic company was determined. The energy from the hot stream was mostly transferred to the cold stream in the ceramic kiln. Energy of the hot stream was created by the rubber wood. This source of energy was to provide to the product manufacturing, heat up the air supply, and cover the heat lost mostly by radiation and emission. The Pinch point was determined when analysing the energy exchange between hot and cold stream in the old type of ceramic kiln in Vietnam. This study resulted in the opening opportunity to enhance the energy efficiency and optimising energy usage in the old type of ceramic kiln using rubber wood as the combusting material.

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